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Measuring the Possibilities of Interfuel Substitution

Robert Bacon

Whether fuel taxes can reduce air pollution cheaply through fuel substitution depends on how flexible activities are with regard to the fuel used. The author reviews empirical methods and findings.

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This paper — a project of the Public Economics Division, Country Economics Department — is part of a larger effort in the department to study pollution control policy in developing countries. The study was funded by the Bank's Research Support Budget under research project "Pollution and the Choice of Policy Instruments in Developing Countries" (RPO 676-48). Copies of this paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Peggy Pender, room N10-067, extension 37851 (November 1992, 76 pages).

What are the costs of making consumption or production activities use less-polluting fuels? Bacon reviews how the fuel mix used by different industries has changed over time and examines two techniques for estimating the responsiveness of fuel demand to fuel prices: econometric models and the engineering approach.

With econometric models, the elasticity of substitution between energy and other inputs determines the costs of making activities less energy-intensive, while the elasticity of substitution between sources of energy (interfuel substitutability) determines the marginal costs of replacing one energy source with another.

The engineering approach uses more detailed technical information and can draw a more complete picture, but with less ability to inform about activities with a vast number of different economic agents.

Among Bacon's main conclusions:

• There are surprisingly large variations in energy and fuel use over time and between countries. Industrial output increased 62 percent in OECD countries between 1971 and 1988, for example, while energy use stayed unchanged! Also, shares of energy sources for industry and electricity vary greatly with local availability, indicating that these sectors have some flexibility in choice of energy source. A judgment on whether this variability indicates that an economy responds cheaply if energy prices are changed selectively depends on how one reads the more detailed studies in the econometric and engineering literature.

• Lack of data is the biggest problem in estimating fuel and energy substitutability in non-OECD countries.

• Engineering studies of fuel switching in industry are rarely available. They exist, however, for the power industry and could be used to estimate the costs of alternative fuel-mixes for particular greenfield sites. The technique could not be used for assessment of economywide policies.

• Econometric studies are useful inasmuch as they take a sector- or economywide perspective. Econometric techniques are challenging, but often represent the state of the art in providing reliable estimates for elasticities of substitution — particularly when data are scarce and the level of aggregation is high.

• The issue of whether econometrically estimated structural parameters can be transferred across borders has not been thoroughly investigated.

MEASURING THE POSSIBILITIES OF INTER-FUEL SUBSTITUTION

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1. INTRODUCTION

In studying the use of policy instruments for reducing pollution in the most practical fashion, attention has been focussed on the possibility of encouraging fuel substitution as a feasible approach. Power generation and several industrial processes (as well as domestic heating) can use alternative fuels. Since the pollution characteristics of fuels vary very widely, an effective fuel switching program could often make a substantial contribution to the reduction of pollution in a region and in a country as a whole.

Two important and inter-related issues are involved in this process. The first is the purely technical issue of the extent to which a process can be switched to a different fuel, and the second is that of the size of incentives/disincentives required to bring about such a substitution. By looking at existing experience it will be possible to obtain evidence on both the extent to which fuel switching might occur and also the degree of price intervention that would be needed to bring this about.

Section 2 reviews the available evidence on fuel mix and its change over time: such data will form a benchmark for assessing the potentiality for change in a given country or industry.

The third section reviews econometric models of fuel substitution and their analytical properties. This is compared and contrasted with the engineering approach which, through a form of cost/benefit analysis, seeks to identify for a given plant the prices at which the optimal fuel choice would switch.

The fourth section reviews actual evidence on price elasticities for fuel switching and discusses how such data might be used in an assessment of the potential for fuel switching.

The main conclusions of the paper can be summarized as follows:

(i) The central problem of evaluating a potential pollution reduction program through price related incentives in countries outside the O.E.C.D. is lack of information. An economy wide program requires data on the whole industrial and power sectors in various forms. For econometric analysis time series of fuel shares in industry (preferably disaggregated) and in power are required, while for micro-based engineering studies data on a large number of plants would be required.

(ii) Given the difficulty of obtaining such data an attractive alternative would be to use elasticities or fuel switching prices estimated from those countries where data is more readily available. However from the issues surveyed in this paper it appears that the opportunity to "import" reliable information of this type may be very limited.

(iii) Engineering studies on fuel switching in industry are rarely available. Technology is so specific to the process studied that the lack of homogeneity in output makes this option of very little interest for extrapolation.

(iv) Engineering studies of fuel switching in power generation do exist in large numbers. The simpler type of study compares the total costs of alternative methods of generating a given amount of power on a greenfield site. The availability of standard cost and operating data as well as local fuel costs and associated infrastructure costs allow a series of alternative scenarios to be evaluated and the price at which (ex ante) fuel switching would just be worthwhile to be identified. This approach is clearly of value in that it can be readily extrapolated to any country or situation by altering a few parameters (e.g. fuel prices at the burner tip). Variations in local conditions may imply that there is no general answer, but the implied spread sheet methodology would be easy to use and some of the key parameters (capital costs and technical performance of alternative technologies) would be universal. The limitation of this type of analysis is that it is really applicable only in a very special situation. A program to reduce pollution could well be economy wide, which would involve all plants in the power generation system. The need to consider the system raises two crucial points for the power sector. First, much of the capital is already installed so that reducing pollution would involve conversion or scrapping decisions - both of these require information on the system in a particular country. Secondly, the fact that the power industry is in practice operated interdependently because of peak loads and uncertain demand, means that in considering whether to alter one plant (or even how to add capacity) the total system requirements need to be taken into account. Such a procedure is well established in power system planning, but the implication is that there is no simple or general guide to the prices at which various amounts of fuel substitution take place - the answers are system specific.

(v) Econometric studies of fuel switching in both the power and industrial sectors have been carried out for the industrialized countries. An attractive feature of the econometric approach is that it is not (typically) plant level, but rather is for the whole economy. It gives an average response which in principle could be used for economy wide policy analysis. There are two key issues which must be resolved satisfactorily before such estimates can be used:

(a) are the estimated values an accurate guide to what is the actual situation in the country of study?

(b) can estimates from one country or industry be used as reliable guides for another country or industry?

(vi) The problems of the econometric approach are reviewed in some detail. For studies pertaining to a given country four issues appear to be important in assessing the reliability of the estimates:

(a) The choice of functional form: this has been the topic of greatest concern. Different flexible cost functions have been estimated. A common feature is the property of non-constant elasticities of substitution. If such functions are used then the elasticities vary with the fuel shares at which they are evaluated - there is no unique elasticity of substitution; simple comparisons between industries, time periods or countries are not meaningful unless allowance is made for this factor. Recent work suggests that, at a given fuel share, the elasticities are fairly robust with respect to the choice of flexible functional form, although the work of Considine, using a completely new functional form, does not fully support this view.

(b) The dynamics of the fuel choice response: early studies showed that pure time series data tended to yield lower price elasticities than cross-section data. This has been interpreted as suggesting that the period of adjustment is lengthy so that static models may well underestimate the total responsiveness of fuel choice to price changes. Little systematic investigation of this issue has been undertaken, but recent models which allow for a crude dynamic adjustment through an autoregressive error process do yield values substantially higher than some earlier studies.

(c) The level of aggregation of the industrial sector: the shifts in industrial composition over lengthy time periods could imply aggregation bias for elasticities if the values for individual industries are substantially different. The recent work on Canadian manufacturing suggests that the values are very similar when evaluated at their fuel shares for the same year, so that estimates which were based on the aggregate sector may not be strongly dependent on the estimation period for reasons of changing aggregation.

(d) The stability of estimates: much of the econometric estimation of fuel price elasticities has been based on data which finished in the 1970s or early 1980s. Given the very large oil price rise at the end of this period, and the likelihood that full adjustment is a lengthy process, it seems that were the structural cost parameters to have changed then this would not have been captured by such estimates. There has been apparently no check on structural stability and, only in the most recent studies has an attempt been made to allow for shifts in the cost function induced by technical progress. Even if there is insufficient data to test for structural stability, it would be desirable to base estimation on data including as much of the recent past as possible.

Within the limitations implied by such comments it does appear that the econometric approach is well established and capable of giving reliable elasticities of substitution at an aggregate level.

(vii) The issue of whether structural parameters are similar for different countries has received rather little attention. Models which have pooled data and provided different elasticities have done so on the basis of evaluations at different market shares, rather than on allowing the cost functions to differ. Problems of degrees of freedom have previously made this an impractical task, but with the accumulation of larger time series it should be possible to attempt tests for equality of cost structures, and hence for implied equality of elasticities at the same fuel shares. A major gap in evidence is the lack of such studies applied to countries outside the O.E.C.D. At present if a model is to be used it would have to be based on highly industrialized countries.

(viii) Econometric studies of the power sector are much less common so that there is less experience on their performance even in advanced economies. Here there are difficulties, even at an economy wide level caused by existing patterns of fuel use:

(a) many countries, as documented in section 2, only use a subset of the three basic fuels for power generation. This leads to modelling difficulties that have largely been ignored in the use of models which are based on the use of all the fuels. This is of particular importance when the aim might be to induce the choice of a fuel not previously utilized.

(b) the use of hydro, nuclear and biomass for power generation has not been explored in econometric modelling of power generation. Studies so far have confined themselves to shares of gas, coal and oil. The nuclear decision may have had a large political element in industrial countries, although it is irrelevant to most developing countries at this stage. Hydro power is seen as being so attractive that it is automatically used first where available and there is no question of price driven substitution. Biomass is unimportant in the industrialized world, but plays a role in fuel choice in many developing countries. Here the problem may be to identify the price of the fuel itself.

(ix) It would appear that there is certainly insufficient evidence on the quantitatative aspects of fuel switching to assess the potential for government price based policies without further research. The nature of the research needed depends on the nature of the policy envisaged. A specific power plant oriented policy would be best served by an engineering study where an initial assessment might well be based on existing calculations which were not system specific. If the initial assessment appeared to indicate a viable program then a more detailed on the spot study would be needed. For individual industrial plants it appears that a detailed study would be needed in any case. For economy wide policies an econometric study of the country in question could be undertaken if there were sufficient data available. This should be possible for both the power and industrial sectors in the case where the attractive fuel was already in use. Where it had not previously been used it might be possible to carry out econometric investigations for similar countries where the fuel was already in use.

(x) For small economies it might be possible to carry out a parallel investigation of fuel choice in the power sector using both econometric and engineering fuel price switching analysis on an ex post basis. Only with such an investigation would it be possible to know whether the various simplifications introduced in econometric modelling distort the quantification of the potential for fuel switching.

2. EVIDENCE ON INTER-FUEL SUBSTITUTION

In order to assess the economic viability of pursuing a fuel switching program it is necessary to have some assurance that it is possible to change the proportions of different fuels used as inputs to different processes. Some aggregate evidence can be obtained by examining country statistics disaggregated by use sector and over time.

The most comprehensive energy statistics available are those for the twenty-five countries covered by O.E.C.D. publications. These exist on a comparable basis for a lengthy period of time (more than twenty years) and have the greatest degree of disaggregation. Accordingly these are taken as a benchmark for investigation of fuel switching in a wider context. The O.E.C.D countries are the highest income and most industrialized nations and many are rich in natural sources of energy so that their patterns of energy use are not likely to be typical of that of the rest of the world. Nevertheless the variations shown both between countries and for a given country over time will indicate the potential at high income standards for variations in fuel use.

Fuel Use in the O.E.C.D.

The starting point for the analysis is the overall breakdown of fuel use by sector for the whole of the O.E.C.D. in a recent year. Table 2.1 shows the use of various forms of fuel as inputs into different sectors of the economy. Each fuel is converted into tons of oil equivalent (to compare the amount of fuel to provide the same energy output) using standard conversion factors.

These figures for a recent year, well after the effects of the two oil shocks have had time to take effect in producing substitution away from oil, indicate several important features of the overall energy market.

(i) In transport and agriculture oil is still the dominant fuel. Substitution between fuels in these sectors has not responded much to the enormous price shifts of the past. Clearly the technological advantage of oil in these sectors is such that fuel substitution will not respond easily to price incentives, although the growth of the sector as a whole and hence their use of energy may respond to fuel prices.

Table 2.1: The Use of Fuel by Sector in the O.E.C.D. in 1988
(Million tons of Oil Equivalent: MTOE)

	Coal	Other Solid Fuel	Oil	Gas	Electricity	Total
Industry	168.85	69.86	297.73	234.56	195.42	949.38
Transport	0.13	0.00	861.13	0.40	6.05	867.71
Agriculture	0.21	0.44	40.72	3.48	3.76	48.61
Commerce/Public Sector	4.18	0.17	86.24	87.72	121.42	302.06
Residential	17.48	43.56	117.34	198.56	150.49	529.58

Source: Energy Balances of the O.E.C.D. countries, 1987- 988, I.E.A. 1989.

(ii) The residential and commercial sectors are both of considerable importance and use substantial amounts of oil, gas and electricity. These sectors are likely to be relatively less important in developing countries where commerce and home heating is typically much less developed.

(iii) The industry sector is the largest, and overall is the only sector to use substantial amounts of coal. Since coal tends to have the worst pollution characteristics this sector is of key importance for studying the potential for fuel switching.

(iv) Electricity, which is a secondary fuel, using the other primary fuels for its generation, is very important when viewed in total. Nearly 500 MTOE of electricity is used so that the fuel mix in this single intermediate sector is worth studying.

These figures show that the key sectors for study are industry and power generation, although more evidence is required to show the potential for change within these sectors.

Changes in Fuel Use in the O.E.C.D.

The lengthy run of consistent data published by the I.E.A. from the O.E.C.D. countries allows a comparison to be made between 1971 and 1988. The earlier year is before the first oil shock so that changes between the two dates reflect changes due both to growth and to shifts in the price of fuel to other inputs and in the relative price of fuels. Table 2.2 gives data on shares of fuel use by the industrial sector.

Table 2.2: Shares of Fuel Use by Industry in MTOE for the O.E.C.D. in 1971 and 1988

	Coal	Other Solid Fuel	Oil	Gas	Electricity	Total (MTOE)
1971	20.2	3.5	39.7	23.1	13.4	946.95
1988	17.8	7.4	31.4	24.7	20.6	949.38

Source: As for Table 2.1.

This table reveals two key points for the study of fuel substitution over the period:

(i) The effects of the increase in fuel prices relative to other input prices have been so strong that, despite the very substantial growth in the industrial sector as a whole of 62%, no more fuel was used as an input in 1988 than in 1971. Without the growth in the sector the use of fuel would have declined substantially.

(ii) As between fuels there has been a strong move away relatively (and absolutely) from the use of oil in industry as a primary fuel.

In addition it can be seen that:

(iii) The total use of solid fuel has increased slightly, which has implications for pollution.

(iv) The use of gas has also increased but only by a small amount, which is interesting given the discoveries of substantial gas resources in several O.E.C.D. countries.

(v) The main increase in fuel use is from the secondary source of electricity. Without an analysis of the fuel mix for power generation it is not possible to see whether in fact there has been substantial switching between primary fuels.

For the public power generation sector in the O.E.C.D. the shares of primary fuels used in 1971 and in 1988 are shown in Table 2.3.

Table 2.3: Shares of Fuel Used for Power Generation in the Public Sector in the O.E.C.D.

	Coal	Other Solid Fuel	Oil	Gas	Nuclear	Hydro	Total MTOE
1971	38.6	0.1	19.9	14.1	2.9	24.2	301.0
1988	42.4	0.2	7.5	8.3	24.3	17.3	528.6

Source: As for Table 2.1.

In relating this table to the two previous tables it is important to bear in mind two limitations imposed by the nature of the data. Firstly, this is for public sector power generation rather than total power generation as in table 2.1. Secondly, table 2.3 is for all uses of electricity rather than for the use by the industrial sector as in table 2.2. However since all end uses of electricity in a given system can be assumed to use the same fuel mix, the relative shares in table 2.3 can safely be taken as representative of the use by industry. Private sector power generation may have a different pattern of primary fuel use, but its relative unimportance (about 5% in 1988) allows the figures of table 2.3 to stand for those of the whole power sector.

The data in table 2.3 reflects the increase in the total use of electricity both relatively, as in industry, and absolutely as in other sectors. The shares of primary fuels show the great decline in the share of oil and more surprisingly declines in the shares of gas and hydro. At the same time the share of solid fuel increased slightly while the share of nuclear increased enormously. The decline in the shares of gas and hydro are not associated with an absolute reduction in their use - rather they have captured in effect very little of the increase in the generation of electricity. The major changes in absolute terms have been the fall in the use of oil and the increase in nuclear.

The rise in nuclear reflects political decisions taken in several O.E.C.D. countries to opt for this form of generation. Often the timing of these decisions go back many years and with the increased concern over safety it is possible that this pattern will not be repeated in countries industrializing at later dates.

The fall in the share of oil relative to all other fuels does indicate that within the power generation sector there is scope for fuel substitution although, if nuclear is netted out, most of this was towards solid fuels rather than gas.

The picture for the O.E.C.D. industrial sector as a whole shows a double substitution away from oil both as a primary fuel and as a secondary fuel through its decline in power generation. Solid fuels have shown a substantial increase on both counts, while gas shows a modest increase through its share in the increased use of electricity. Tables 2.2 and 2.3 could be combined to give the total primary fuel use by industry if an energy loss figure between the input and output of power generation were available for the two dates.

In order to place these quantity shifts in focus it would be useful to know the behavior of fuel prices for the O.E.C.D. as a whole. There are no published aggregate fuel prices so that a full picture cannot be given. However for the U.S.A. there are prices available for the different fuels as purchased by steam raising electric utility plants. Table 2.4 gives data on these for the widest span of years available (1973 and 1988) and also for the intermediate year 1981 when the oil prices were at their peak.

Table 2.4: Cost of Fossil Fuels at Steam Electric Utility Plants in Cents/BTU for the U.S.A.

	Coal	Heavy Fuel Oil	Gas	All Fuels	Industrial Good Prices Index
1973	40.5	78.5	33.8	47.6	100.0
1981	153.2	533.4	280.5	225.6	241.5
1988	46.6	240.5	226.3	164.3	263.9

Source: (EIA Monthly Energy Statistics).

This table shows firstly that fuel prices rose very sharply relative to other prices in the period 1973 to 1981 but fell back some of the way by 1988. The price of heavy fuel oil relative to coal nearly doubled in the first period but fell to a low level by 1988, while the price of heavy fuel oil relative to gas fell throughout the period (the price of coal relative to gas rose slightly in the second period). Although the U.S.A. is not representative of all countries in the O.E.C.D. it is by far the largest user of energy so that these figures are suggestive. There was a sharp increase in the relative cost of fuel associated with the two oil 'shocks', but by 1988 much of this had been reversed. However, with investment taking time to plan and install, the reaction to the fuel price decline may not yet be fully felt. There were also large shifts in relative fuel prices. The degree of fuel switching that this induced will again be difficult to assess because of the need to take into account lags in adjustment. This has important implications for econometric modelling.

Total Industry Disaggregation by Country within the O.E.C.D.

The picture so far established is for the O.E.C.D. as a whole. This grouping of countries certainly includes a considerable degree of heterogeneity.

For industry as a whole the fuel shares for 1988 are shown for each country in table 2.5.

Table 2.5: Fuel Shares in Industry for O.E.C.D. Countries, 1988

	Coal and Other Solid Fuels	Oil	Gas	Electricity
Australia	31.7	16.4	29.7	22.2
Austria	32.5	16.8	27.1	23.7
Belgium	29.5	28.0	22.9	18.2
Canada	19.6	21.5	33.1	25.0
Denmark	16.8	40.1	14.2	26.6
Finland	44.0	19.8	7.5	27.5
France	21.0	34.2	23.7	21.0
Germany	24.7	30.0	22.4	22.8
Greece	27.7	45.5	2.4	24.3
Iceland	16.7	25.0	0.0	61.1
Ireland	19.5	35.7	30.3	14.5
Italy	11.6	34.4	32.2	21.7
Japan	29.4	41.3	3.0	26.3
Luxembourg	58.8	15.8	11.5	3.9
Netherlands	10.8	34.9	41.0	13.2
New Zealand	34.0	7.5	32.7	25.7
Norway	17.1	31.5	0.0	51.2
Portugal	24.2	58.2	0.0	16.9
Spain	19.6	47.8	10.5	22.1
Sweden	38.5	24.0	1.4	35.2
Switzerland	14.9	31.3	15.8	36.5
Turkey	41.0	40.7	1.4	16.9
United Kingdom	21.0	32.6	27.6	18.7
U.S.A.	26.2	24.8	32.2	16.8
Yugoslavia	12.9	27.2	29.6	24.3
O.E.C.D.	25.2	31.4	24.7	20.6

Source: As table 2.1.

This table shows that for industry as a whole there are very substantial variations in fuel shares between the industrialized countries at the same point in time. However these variations cannot be taken literally as defining a range of variations that is available for each and every country. Two major influences on fuel share may be largely country specific, thus placing limits on the potential for fuel switching:

(i) the local availability of primary sources of energy. Although oil is freely traded and coal is also often traded, the trade in gas in much more limited by the enormous infrastructure costs involved. Countries with their own gas reserves (e.g. U.S.A., U.K., Netherlands) or very near to gas reserves tend to use much more gas than those far distant from such reserves (e.g. Iceland or Portugal).

(ii) the industrial mix plays an important role in determining fuel share as shown below. If different industries tend to favor different fuels then the pattern of industrial specialization will be important in explaining the fuel shares in the total industrial sector. Since the industrial pattern responds to many other factors than the relative price of different fuels, it is unlikely that it would be possible, by changing the attractiveness of different fuels, to achieve the range of variations in fuel use illustrated across the range of O.E.C.D. countries. It is possible to give equivalent figures for an earlier date, but given the large changes in industrial structure that have taken place over the last twenty years in many countries this is left to the more disaggregated analysis below.

Fuel Shares in Electricity for Individual O.E.C.D. Countries

The use of primary fuels for power generation (valued in MTOE) is available over a long period of time for all the O.E.C.D. countries. Since power generation is a single industry there is no problem of changing shares of output to contend with as for the total industrial sector. Table 2.6 gives shares for 1970 and table 2.7 shares for 1988.

Table 2.6: Shares of Primary Fuels in Power Generation for O.E.C.D. Countries in 1971

	Coal and Other Solid Fuels	Oil	Gas	Nuclear	Hydro
Australia	75.60	4.62	0.86	0.00	18.39
Austria	9.56	6.91	12.21	0.00	70.72
Belgium	33.64	52.08	13.29	0.19	0.81
Canada	17.91	3.06	3.04	0.49	75.49
Denmark	31.21	68.67	0.00	0.00	0.12
Finland	20.20	27.55	0.00	0.00	42.10
France	30.22	21.97	4.50	3.89	38.94
Germany	68.62	15.00	5.53	2.49	7.32
Greece	38.32	34.84	0.00	0.00	26.84
Iceland	0.00	2.96	0.00	0.00	97.04
Ireland	1.24	53.79	0.00	0.00	13.85
Italy	4.8	48.80	4.85	2.70	37.49
Japan	16.72	58.47	1.25	1.28	22.28
Luxembourg	47.21	11.41	0.09	0.00	41.29
Netherlands	19.81	32.60	46.69	0.90	0.00
New Zealand	6.12	3.31	0.06	0.00	90.51
Norway	0.00	0.63	0.00	0.00	99.37
Portugal	4.90	14.44	0.00	0.00	78.18
Spain	21.65	27.14	0.01	1.63	49.49
Sweden	0.28	30.92	0.00	0.09	68.49
Switzerland	0.00	5.92	0.00	4.98	89.10
Turkey	34.55	30.30	0.00	0.00	35.15
United Kingdom	68.48	18.48	0.33	10.44	2.27
U.S.A.	46.39	12.12	24.58	1.44	15.46
O.E.C.D.	38.70	19.90	14.10	2.90	24.20

Source: As for table 2.1.

Table 2.7: Shares of Primary Fuels in Power Generation for O.E.C.D. Countries in 1988

	Coal and Other Solid Fuels	Oil	Gas	Nuclear	Hydro
Australia	75.84	1.85	10.81	0.00	11.16
Austria	8.97	4.21	10.14	0.00	75.75
Belgium	24.81	2.63	3.90	65.96	1.79
Canada	18.51	2.41	1.42	16.43	60.79
Denmark	93.30	4.55	0.94	0.00	0.13
Finland	18.67	2.66	4.89	36.37	24.85
France	7.31	1.50	0.56	70.30	20.10
Germany	51.14	2.58	6.80	33.65	4.80
Greece	73.03	18.91	0.28	0.00	7.78
Iceland	0.00	0.16	0.00	0.00	99.84
Ireland	56.90	7.33	26.67	0.00	9.11
Italy	16.70	44.12	15.93	0.00	22.91
Japan	14.94	29.07	19.38	23.70	12.90
Luxembourg	28.85	4.28	1.43	0.00	61.98
Netherlands	35.71	5.45	52.33	5.28	0.00
New Zealand	2.08	0.00	17.29	0.00	80.63
Norway	0.04	0.35	0.00	0.00	99.56
Portugal	26.82	15.57	0.00	0.00	54.71
Spain	31.28	5.07	0.80	36.37	26.09
Sweden	1.29	1.58	0.06	47.37	48.31
Switzerland	0.05	0.47	0.43	37.55	60.64
Turkey	25.99	6.88	6.74	0.00	60.39
United Kingdom	67.05	9.48	0.62	20.59	2.26
U.S.A.	57.31	5.54	9.42	19.45	8.22
O.E.C.D.	42.60	7.50	8.30	24.30	17.30

Both tables show that at a given point in time there are enormous variations between countries in the fuel mix used for power generation. The most extreme examples of this are those countries where there are suitable conditions for the use of hydro: in Iceland, Norway and New Zealand virtually all power came from hydro even in 1988. Natural resource endowment is certainly a crucial factor in explaining the choice of fuel.

Comparing the two tables shows that in the power sector the principal change in share has been the increase in nuclear generation for certain countries (e.g. Belgium, France and Sweden). Some countries have not chosen this route (even excluding those with abundant hydro power e.g. Australia, Denmark and Italy) and this suggests that the decision to move to nuclear has been largely determined outside strict cost conditions (nuclear being in effect a highly traded product with few countries being so abundant in the raw material that there is a local cost advantage). In countries which did not opt for nuclear power during this twenty year period there has certainly been substantial inter fuel substitution. For example, Australia decreased the share of oil and increased that of gas, while Denmark and Greece switched from a heavy reliance on oil to coal and solid fuel. The picture from O.E.C.D. countries is that within the homogeneous power generation sector not only is fuel substitution possible, but that it actually took place and that in some countries there was an extraordinary shift in the fuel mix used.

Fuel Shares in Various Industries in the O.E.C.D.

As argued above the industrial sector is the major user of energy and fuel substitution in this area is of great importance for policy purposes. However the figures for the aggregate sector are not a complete guide to fuel choice since different industries have very different patterns of fuel choice. Hence shifts in the relative importance of an individual sub-sector (e.g. the decline in iron and steel in many industrialized countries) will produce changes in aggregate fuel mix which are unrelated to the possibilities for fuel switching to produce a given level of output.

Data is available for a sub-set of the O.E.C.D. on fuel use by industrial sub-sectors. Table 2.8 shows fuel shares for O.E.C.D. Europe for thirteen industries in 1988.

These sectors, which vary considerably in the technologies used, show considerable variations in their fuel mix. Excluding chemical feedstock, in which the oil and gas are converted into other products, there is still a great variation from the very coal intensive iron and steel industry to the electricity intensive non-ferrous metals industry. This table does not of course show the possibilities of fuel substitution, since the technologies used are often industry specific; it does however show the dangers of using trends in aggregate industrial fuel shares to indicate substitution possibilities. Changes in industrial mix could obviously bring about large changes in aggregate fuel mix without any fuel substitution taking place at a plant level. Of course factors

Table 2.8: Fuel Shares in Various Industries in O.E.C.D. Europe in 1988

	Coal and Other Solid Fuel	Oil	Gas	Electricity	Energy Shares in Total Industry
Total	22.7	33.4	21.6	22.2	100.0
Iron and Steel	64.7	8.0	12.0	15.3	18.5
Chemical Feedstocks	0.0	83.0	17.0	0.0	17.1
Other Chemicals	11.9	26.0	32.0	30.0	16.2
Non-ferrous Metals	6.6	16.8	13.2	63.3	3.8
Non-metallic Minerals	28.6	30.8	26.8	13.8	10.7
Transport Equipment	4.1	17.0	31.1	47.7	2.1
Machinery	4.5	26.2	32.8	36.5	5.2
Mining/Quarrying	6.1	33.2	14.6	45.7	1.0
Food/Tobacco	8.9	32.6	32.3	26.2	6.5
Paper/Printing	29.5	16.6	18.6	35.1	7.2
Wood/ Wood Products	37.0	15.9	5.3	41.5	1.2
Construction	20.0	61.9	3.5	14.6	1.6
Textiles/Leather	6.1	34.4	23.7	36.0	2.7

Source: As table 2.1.

which bring about changes in industrial structure will bring about changes in aggregate fuel mix, but such changes are not likely to be brought about by a desire to alter the overall pollution characteristics of an economy apart from exceptional cases. The projected decline of certain heavy industries in Eastern Europe is being welcomed as a positive contribution to reducing the very high levels of pollution in certain areas (Hughes [1991]).

Comparison of the disaggregated industrial data for 1988 in table 2.8 and that for 1970 shown in table 2.9 does allow an insight into the possibilities of fuel switching for a specific type of technology. However it must be noted that even for industrial data disaggregated into 13 sectors there will still be some changes due to the particular product composition changing within a given sub-sector.

Table 2.9: Fuel Shares in Various Industries in O.E.C.D. Europe in 1970

	Coal and Other Solid Fuel	Oil	Gas	Electricity	Energy Shares in Total Industry
Total	27.0	50.7	8.5	13.8	100.0
Iron and Steel	63.7	19.8	7.3	9.2	25.3
Chemical Feedstocks	0.0	99.7	0.3	0.0	8.2
Other Chemicals	17.5	40.8	21.3	22.5	14.8
Non-ferrous Metals	20.9	22.1	8.0	49.0	2.7
Non-metallic Minerals	20.7	54.2	15.1	9.9	8.9
Transport Equipment	13.8	58.0	3.9	24.3	1.3
Machinery	9.5	54.3	22.9	13.2	3.3
Mining/Quarrying	1.7	60.5	10.3	27.1	0.9
Food/Tobacco	13.4	64.9	8.2	13.5	4.7
Paper/Printing	11.5	56.2	5.7	26.7	4.6
Wood/ Wood Products	58.2	33.0	0.3	8.5	1.0
Construction	0.0	88.8	0.7	10.5	0.5
Textile/Leather	6.1	72.6	6.4	14.9	1.9

This table illustrates the substantial changes in the relative importance of the different industries (particularly the rise in the chemical feedstock industry and the decline in iron and steel). Within industries there has also been substantial change in the fuel mix used. In every case the relative importance of oil has declined sharply and the shares of gas and electricity have increased. For coal the picture is more variable. In some industries (chemicals, non-ferrous metals, transport equipment and wood) the share has decreased, while in others (non-metallic minerals and paper) it has increased (the figure for the construction industry in 1970 must be treated with caution). These tables indicate that there was strong fuel substitution within industries and that different patterns occurred in the various sub-sectors. This suggests that the potential for encouraging fuel substitution in other countries may be very promising.

The experience of the O.E.C.D. points to certain broad conclusions which have relevance for other countries:

(i) changes in the price of energy to other goods can produce large changes in energy intensity (ratio of energy to output). Any policy which alters the price of energy as a whole is likely to have important effects on the total amount of energy used and hence on the amount of pollution;

(ii) there have also been large swings in the relative prices of different fuels coupled with large shifts in relative fuel use. The exact effects depend crucially on the lags involved so that to evaluate the full potential of a fuel switching policy it is necessary to know the speed of adjustment to the policy change;

(iii) some of the biggest differences in fuel use between countries are associated with the domestic availability of the various fuels. Any fuel switching policy must allow fully for the price advantage of domestic as opposed to imported fuels.

Fuel Use Outside the O.E.C.D.

The evidence so far presented relates to the most developed sector of the world economy, for which the statistics are the most adequate. However, the focal point of interest is countries at earlier stages of development. Some O.E.C.D. countries (e.g. Greece and Portugal) in the early 1970s were at a stage of development not very different from many other countries at the present day, but it would be unwise to draw too strongly on their experience which may have been dominated by special factors.

There is data on a wide range of countries published by the United Nations in "Energy Balances and Electricity Profiles". This covers 48 non O.E.C.D. countries for industry data and 75 non O.E.C.D. countries for power generation data. The time span of years available is much shorter so that the evidence on fuel substitution within countries on a consistent basis is rather limited.

Fuel Use in Industry Outside the O.E.C.D.

Table 2.10 gives the shares of different fuels used by industry for 1986 where all fuels have been converted into energy equivalent units (tetrajoules). An important difference from O.E.C.D. experience is the use of bio-mass which in many cases is very significant and is shown separately.

Table 2.10: Shares of Fuels in the Industrial and Construction Sectors for Certain Non-O.E.C.D. Countries in 1986

	Coal	Oil	Gas	Electricity	Biomass
Argentina	2.9	22.5	46.6	16.4	11.3
Bangladesh	6.0	10.4	35.1	14.3	34.3
Barbados	0.0	14.2	8.4	17.8	59.6
Bolivia	10.8	32.6	12.9	10.7	33.0
Brazil	16.3	19.1	5.8	22.7	36.1
Chile	20.8	38.2	4.4	23.0	13.6
Colombia	41.3	14.7	16.6	12.0	15.2
Costa Rica	1.1	0.0	0.0	33.7	65.2
Ivory Coast	0.0	69.4	0.0	11.8	18.8
Cyprus	14.2	76.8	0.0	9.0	0.0
Ecuador	0.0	62.6	0.0	15.2	21.4
Egypt	6.0	59.7	15.3	14.0	4.9
El Salvador	0.0	32.2	0.0	10.8	56.1
Fiji	4.9	3.8	0.0	10.0	81.2
Gabon	0.0	64.8	25.3	8.0	1.9
Honduras	0.0	32.4	0.0	9.5	58.1
Hong Kong	1.9	72.5	0.4	25.2	0.0
India	68.5	10.8	2.7	11.1	7.0
Indonesia	2.7	48.1	32.1	6.9	10.1
Israel	0.0	68.2	2.6	29.1	0.0
Jamaica	0.0	76.5	0.0	13.3	10.1
Jordan	0.0	87.7	0.0	12.3	0.0
Kenya	13.4	25.6	0.0	27.8	32.1
South Korea	27.0	52.7	0.0	19.3	0.0
Kuwait	0.0	42.4	55.5	2.1	0.0
Malawi	12.1	2.9	0.0	12.3	72.7
Malaysia	8.2	65.2	10.4	14.8	1.2
Morocco	3.5	78.4	6.4	11.7	0.0
Nepal	25.9	12.4	0.0	10.5	51.1
Nicaragua	0.0	26.5	0.0	7.2	65.4
Niger	0.0	42.2	0.0	57.8	0.0
Nigeria	1.5	57.8	35.5	4.4	0.7
Pakistan	26.5	15.2	35.7	10.2	12.4
Papua N.G.	0.0	28.3	0.0	26.9	44.2
Peru	2.6	55.2	2.3	24.6	14.0
Philippines	17.8	39.7	0.0	16.9	25.0
Qatar	0.0	0.0	97.8	2.2	0.0
Saudi Arabia	0.0	81.0	14.0	5.0	0.0
Singapore	0.0	86.1	0.0	13.9	0.0
Solomon Islands	0.0	95.9	0.0	4.1	0.0
Sri Lanka	0.2	21.4	0.0	11.7	66.7
Thailand	6.1	29.8	1.7	16.3	46.0
Trinidad	0.0	68.9	23.2	5.8	2.1
Tunisia	5.9	57.8	19.8	16.5	0.0
Uruguay	0.1	34.9	0.2	19.1	45.4
Venezuela	1.1	17.4	59.8	17.7	4.0
Zambia	32.0	16.3	0.0	43.2	7.7
Zimbabwe	58.9	3.7	1.5	17.6	18.4

Source: "Energy Balances and Electricity Profiles", 1986, United Nations.

The table shows an even larger variation between countries in fuel mix than is the case for the O.E.C.D. This reflects in large part the variations in the endowment of natural resources. The oil producers not surprisingly use large amounts of oil and gas, while those countries which do not produce oil use relatively little. Countries where there is ample material for biomass, notably in South America, use this to a great extent. The variations due to endowments may exaggerate the extent to which fuel substitution is economically feasible within a country for likely variations in domestic prices. There will also be very substantial variations in the industrial composition between these countries which accounts for some of the variations in fuel mix. Nevertheless, they do indicate that at a technical level it is possible to use a wide range of fuel mix. This in turn suggests that there is substantial scope to induce such substitution.

The dominant use of hydro power in certain countries and oil in others is, as noted above, related to the domestic availability of the various fuels. This is in effect related to the prices (or potential prices) of the various fuels c.i.f. at the burner tip. If hydro capacity has been installed then its price can be so low (even allowing for the capital cost element) that the price of any imported fuel would be uncompetitive. As well as the general world f.o.b. costs other fuels would need to add on the domestic transport cost margin and associated capital cost where the infrastructure did not already exist (e.g. the costs of a terminal and pipeline for oil or gas). The effective hydro price could be very much lower than the potential oil cost so that a small change in the price of oil relative to hydro would bring no shift in fuel use.

<u>Fuel Use in Power Generation Outside the O.E.C.D</u>.

Data are also available for the fuels used in power generation in the non O.E.C.D. countries. For these countries nuclear is unimportant and hydro is so dependent on natural resources that the availability of figures for thermal

Table 2.11: Fuel Shares in Thermal Power Generation in non O.E.C.D. Countries in 1986

	Coal and Other Solid Fuel	Oil	Gas	Other	Share of thermal in total public power
Algeria	0.0	3.0	97.0	0.0	97.9
Argentina	3.6	42.6	53.8	0.0	40.8
Bangladesh	0.0	25.0	75.0	0.0	90.6
Barbados	0.0	100.0	0.0	0.0	100.0
Belize	0.0	100.0	0.0	0.0	100.0
Benin	0.0	100.0	0.0	0.0	100.0
Bolivia	0.0	56.3	43.7	0.0	22.9
Botswana	100.0	0.0	0.0	0.0	100.0
Brazil	34.1	46.9	0.0	19.0	6.4
Brunei	0.0	7.1	92.9	0.0	100.0
Burma	4.8	30.3	64.9	0.0	50.3
Burundi	0.0	100.0	0.0	0.0	100.0
Central African Republic	0.0	100.0	0.0	0.0	17.2
Chad	0.0	100.0	0.0	0.0	100.0
Chile	54.1	31.4	7.2	7.2	8.8
Colombia	30.6	3.9	65.5	0.0	30.0
Costa Rica	0.0	63.7	0.0	36.3	0.2
Ivory Coast	0.0	100.0	0.0	0.0	22.6
Cyprus	0.0	100.0	0.0	0.0	100.0
Dominican Rep.	0.0	100.0	0.0	0.0	72.9
Ecuador	0.0	100.0	0.0	0.0	15.2
Egypt	0.0	75.4	24.6	0.0	74.4
El Salvador	0.0	100.0	0.0	0.0	3.5
Ethiopia	0.0	100.0	0.0	0.0	14.3
Fiji	0.0	24.2	0.0	75.8	5.7
French Guiana	0.0	100.0	0.0	0.0	100.0
Gabon	0.0	54.5	45.5	0.0	22.5
Ghana	0.0	100.0	0.0	0.0	1.7
Grenada	0.0	100.0	0.0	0.0	100.0
Guatemala	0.0	100.0	0.0	0.0	56.1
Haiti	0.0	100.0	0.0	0.0	23.9
Honduras	0.0	100.0	0.0	0.0	14.1
Hong Kong	72.7	26.3	0.0	0.0	100.0
India	90.2	5.8	4.0	0.0	68.7
Indonesia	14.0	68.4	17.5	0.0	80.9
Israel	58.9	41.1	0.0	0.0	100.0
Jamaica	0.0	97.0	0.0	3.0	90.3
Jordan	0.0	100.0	0.0	0.0	100.0
Kenya	0.0	100.0	0.0	0.0	4.3
South Korea	54.2	44.9	0.9	0.0	50.2
Kuwait	0.0	16.6	83.4	0.0	100.0
Madagascar	0.0	100.0	0.0	0.0	30.3
Malawi	40.7	59.3	0.0	0.0	0.4
Malaysia	0.0	77.6	22.4	0.0	73.3
Mali	0.0	100.0	0.0	0.0	17.7
Mauritius	0.0	100.0	0.0	0.0	72.9
Mexico	5.0	83.0	12.0	0.0	74.0
Morocco	27.1	72.9	0.0	0.0	90.3
Nepal	0.0	100.0	0.0	0.0	0.7
Nicaragua	0.0	88.3	0.0	11.7	43.4
Niger	59.2	40.8	0.0	0.0	100.0

Table 2.11 Cont'd: Fuel Shares in Thermal Power Generation in non O.E.C.D. Countries in 1986

	Coal and Other Solid Fuel	Oil	Gas	Other	Share of thermal in total public power
Nigeria	0.1	19.6	80.3	0.0	77.6
Pakistan	0.6	30.5	68.9	0.0	30.4
Papua N.G.	0.0	100.0	0.0	0.0	27.3
Peru	0.0	83.9	9.2	6.8	10.3
Philippines	21.6	78.4	0.0	0.0	45.1
Puerto Rico	0.0	100.0	0.0	0.0	98.2
Qatar	0.0	6.0	94.0	0.0	100.0
Rwanda	0.0	100.0	0.0	0.0	3.4
St. Pierre	0.0	100.0	0.0	0.0	100.0
Saudi Arabia	0.0	92.8	7.2	0.0	100.0
Senegal	0.0	100.0	0.0	0.0	100.0
Seychelles	0.0	100.0	0.0	0.0	100.0
Singapore	0.0	100.0	0.0	0.0	100.0
South Africa	100.0	0.0	0.0	0.0	96.0
Sri Lanka	0.0	100.0	0.0	0.0	0.3
Sudan	0.0	100.0	0.0	0.0	44.5
Thailand	27.6	19.1	53.3	0.0	77.5
Trinidad	0.0	23.0	77.0	0.0	100.0
Tunisia	0.0	51.3	48.7	0.0	98.6
Uruguay	0.0	64.7	0.0	35.3	0.7
Venezuela	0.0	40.9	59.1	0.0	51.6
Zaire	0.0	100.0	0.0	0.0	3.0
Zambia	66.0	34.0	0.0	0.0	0.2
Zimbabwe	100.0	0.0	0.0	0.0	46.1

Source: As for table 2.10.

power generation is adequate to indicate the range of fuels used in the developing world. Table 2.11 shows the shares for 1986.

The table shows that a very large number, especially of the smaller countries, rely entirely on oil for thermal power generation. In addition there is a much more limited range of fuel used for power generation than for industry (for those countries where data is available on both). Thus, even when all primary fuels are used in industry, often one or two fuels are not used for power. There is clearly potential for substitution. The tendency to rely on one fuel may be due to strong economies of scale in the generating industry in some of the smaller countries so that only with substantial growth could a fuel mix evolve.

The same source gives data on fuel shares into power generation going back to 1976. This date is before the second oil shock but will to a certain extent not fully reflect the impact of the first oil shock, so that the changes, if any, between 1976 and 1986 indicate only part of the substitutability between fuels. Table 2.12 gives fuel shares in power generation for all the non O.E.C.D. countries covered by this U.N. source.

This data for 1976 does not cover such a wide range of countries as that for 1986 and also does not allow for biomass. Nevertheless the picture is very clear. With the exception of a handful of coal or gas producing countries there was almost complete reliance on oil for thermal power generation. Where there were other fuels already used (e.g. Algeria, Argentina, Bangladesh, Brazil, etc.) the share of oil did drop substantially over the ten year period. Many of those countries completely dependent on oil in 1976 continued to be so a decade later despite the oil shocks which spanned this period.

For studying substitution of fuels this appears to point to some important findings. In many countries, either because of their size or because of their distance from the production of competing fuels, there is rather little scope for substitution away from oil in thermal power generation. If the shocks of the 1970s did not produce even a small degree of substitution, then it is likely that a large and expensive intervention would be needed to change the fuel

Table 2.12: Fuel Shares in Thermal Power Generation in non O.E.C.D. Countries in 1976

	Coal and Other Solid Fuel	Oil	Gas
Algeria	0.0	18.0	82.0
Argentina	3.5	73.4	23.1
Bangladesh	0.0	46.4	53.6
Barbados	0.0	100.0	0.0
Belize	0.0	100.0	0.0
Benin	0.0	100.0	0.0
Bolivia	0.0	0.0	100.0
Botswana	100.0	0.0	0.0
Brazil	43.4	56.6	0.0
Brunei	0.0	1.7	98.3
Burma	7.5	50.1	42.4
Burundi	0.0	100.0	0.0
Central African Rep.	0.0	100.0	0.0
Chad	0.0	100.0	0.0
Colombia	26.2	36.9	36.9
Costa Rica	0.0	100.0	0.0
Cyprus	0.0	100.0	0.0
Dominican Rep.	0.0	100.0	0.0
Ecuador	0.0	100.0	0.0
Egypt	0.0	100.0	0.0
El Salvador	0.0	100.0	0.0
Ethiopia	0.0	100.0	0.0
French Guiana	0.0	100.0	0.0
Gabon	0.0	42.6	57.4
Ghana	0.0	100.0	0.0
Guatemala	0.0	100.0	0.0
Haiti	0.0	100.0	0.0
Honduras	0.0	100.0	0.0
Hong Kong	0.5	99.5	0.0
India	87.9	11.0	1.1
Indonesia	0.0	100.0	0.0
Israel	0.0	100.0	0.0
Ivory Coast	0.0	100.0	0.0
Jamaica	0.0	100.0	0.0
Jordan	0.0	100.0	0.0
Kenya	0.0	100.0	0.0
South Korea	9.9	90.1	0.0
Kuwait	0.0	15.5	84.5
Macao	0.0	100.0	0.0
Madagascar	0.0	100.0	0.0
Malawi	14.8	85.2	0.0
Malaysia	0.0	100.0	0.0
Mali	0.0	100.0	0.0
Mauritius	0.0	100.0	0.0
Mexico	0.8	77.3	21.9
Morocco	89.1	10.9	0.0
Nepal	0.0	100.0	0.0
Nicaragua	0.0	100.0	0.0
Nigeria	10.2	7.9	81.9
Pakistan	4.8	1.9	93.3
Panama	0.0	100.0	0.0
Philippines	2.0	98.0	0.0

Table 2.12 Cont'd.: Fuel Shares in Thermal Power Generation in non O.E.C.D. Countries in 1976

	Coal and Other Solid Fuel	Oil	Gas
Puerto Rico	0.0	100.0	0.0
Rwanda	0.0	100.0	0.0
St. Pierre	0.0	100.0	0.0
Saudi Arabia	0.0	71.0	29.0
Senegal	0.0	100.0	0.0
Seychelles	0.0	100.0	0.0
Singapore	0.0	100.0	0.0
South Africa	100.0	0.0	0.0
Sri Lanka	0.0	100.0	0.0
Sudan	0.0	100.0	0.0
Thailand	7.1	92.9	0.0
Tunisia	0.0	46.5	53.5
U. Rep. of Cameroon	0.0	100.0	0.0
Uruguay	0.0	100.0	0.0
Venezuela	0.0	27.9	72.1
Zaire	0.0	100.0	0.0

Source: As for table 2.10.

pattern. Those countries worth studying in detail because of a substantial potentiality for fuel switching in power are relatively few in number.

There has been relatively little systematic study of fuel switching in developing countries for the power and industrial sectors. This is largely because to capture the major changes it would be necessary to have a lengthy time series of data and this in general does not exist. The ten year span of the U.N. data used in tables 2.10, 2.11 and 2.12 is long enough to indicate certain trends, but it is insufficient for more sophisticated statistical work as will be discussed below. Data for a ten year period have been discussed for a series of reports prepared for the Asian Development Bank: Pakistan (Rhee [1986]), S. Korea (Kim [1986]), Thailand (Khumsoong et al. [1986]), India (Bhatia [1986]), Bangladesh (al-Husainy [1986]), and some comparative material on industrial and developing countries is given in Leach, Jurass et al. [1986]. In all of these there is much less detailed data available than for comparable studies of industrial countries.

Despite the lack of detailed industrial disaggregation and the relatively short runs of data available, the figures that are available suggest a number of important features of the mixture of fuels used in industry and in power generation:

(i) Aggregate fuel mix in the industry sector is strongly influenced by the composition of the sector. O.E.C.D. experience suggests that any analysis of changing trends in fuel use in the sector would need to take account of shifts in industrial structure, which in many countries has been strongly affected by the oil shocks as well as by the pace of economic growth. This suggests that it would be necessary to have disaggregated data for a successful investigation of inter-fuel substitution.

(ii) The fuel mix tends to be more evenly spread in the industrial sector than in the power sector, which suggests that there are more possibilities for substitution in industry.

(iii) In countries where a mixture of fuels was used for power generation in the 1970s there is usually evidence of substantial substitution away from oil in the following decade. These countries look to offer the best cases for studying fuel switching.

(iv) Many countries relied entirely on oil for thermal power generation in the 1970s and continued to do so despite the oil shocks. The reasons for this pattern are probably connected with the accessibility of oil compared to other fuels and with the small scale of the power sector which may not have grown enough to permit the use of a second fuel.

3. METHODS FOR ESTIMATING THE SUBSTITUTABILITY OF FUELS

In studying the potential for fuel substitution there are two distinct approaches available. The econometric approach is essentially historical and relates actual experience of fuel switching, usually at a rather aggregate level, to the various factors which may have produced these changes. The engineering approach typically is more prospective, in the spirit of project appraisal, and seeks to describe for a specific situation the cost conditions under which one fuel or another would be used.

Econometric Studies of Fuel Substitutability

Many econometric studies of fuel switching and fuel use have been published and these form a natural starting point for an analysis of methods of measuring fuel substitutability. Interest in the use of fuels began with a series of studies in the 1970s which investigated the impacts of the rise in real energy prices following the first oil shock. A crucial point for such studies was the extent to which energy was a substitute or complement to the other inputs. The methodology developed in these studies was later extended to disaggregating between the different fuels so that it became possible to estimate the degree to which one fuel was switched for another as well as the degree to which fuels were substituted in total against other factors of production.

All econometric studies have made certain assumptions about the nature of the use of energy which are central to the models developed but which are quite different in spirit from the approach of engineering studies, and it is important to highlight these before the more detailed description of the approach is given.

The central assumption is that there is a continuous degree of substitutability between the various inputs. Small changes in external forces, such as relative prices, will then produce small changes in the pattern of energy use and fuel choice. This assumption of continuous substitutability, although very convenient for modelling, does not correspond to a description of what happens at any particular site. In particular cases fuel prices may have to change a great deal before there is any switch to a different fuel, as will be discussed below. The principle defence for the econometric approach is that for an aggregate defined over many plants a small change in price will produce a response at some, but not necessarily all, sites, so that there is always an aggregate response to price changes.

The second distinctive feature of the econometric studies is that typically the link between capital and energy is not formally specified. They are usually viewed as two factors which may or may not be complements or substitutes. If one fuel is to be substituted for another the prices of the fuels are used as explanatory factors but the capital costs of the alternative fuel technologies are not specifically introduced. Instead an aggregate cost of capital is introduced as a separate explanatory factor. This is in sharp distinction to engineering studies where the capital costs of alternative fuel burning technologies are crucial in determining fuel choice. These two aspects of the econometric approach highlight the fact that the technology is not specified, while in engineering studies this is the central point in formulating the optimal choice of fuel.

Early econometric studies on the use of energy as a factor input treated it as a single fuel and concentrated on its relation to capital and labor. Berndt and Wood [1975], Fuss [1977], Magnus [1979] using data for a single country found energy and labor to be substitutes while energy and capital were complements. Fuss also found some substitutability between oil, coal and gas in Canada but none between those fuels and electricity. Halvorsen [1977] found a larger measure of substitutability between all fuels for the U.S. Griffin and Gregory [1976] used cross-section data at five year intervals to capture long run effects and found substitutability between energy and capital.

Griffin [1977] and Pindyck [1979] have provided definitive accounts of the standard econometric approach to modelling the shares of fuels in industry or electrical power generation. Most of the subsequent work refers to the ideas of these studies so a detailed account is given of the approach used by Griffin. The starting point is the production function: the output (Q) is assumed to be a twice differentiable function of the services of capital (K), labor (L) and energy inputs, as well as of technical change (t). In the case of electricity these inputs are denoted by the quantities of coal (Q_c), gas (Q_g) and oil (Q_o). For industry analysis the fourth input, energy (Q_E), would be added. Studies such as Considine [1989] have suggested grouping fuels according to the industry under analysis. Materials (M) can also be allowed for, as in Pindyck, by assuming that it is "weakly separable" from the other inputs as a group - this in effect allows materials to be ignored which is necessary at an aggregate level because of lack of data. The differentiability of the production function implies that there is continuous substitutability between the various inputs. The production function describes the output which will be obtained from the various combinations of inputs. Corresponding to this is a cost function (C) which describes the cheapest total cost of producing a given output with the given prices of the various factors of production. In studies of the energy market analysis almost invariably focuses on the cost function approach.

The general form of the cost function is written:

$$C = C(P_K, P_L, P_C, P_G, P_O, t, Q) \qquad (1)$$

where P_i denotes the price of input i. The functional form of the cost function is a key issue for econometric modelling. The cost function must be homogeneous of degree 1 in prices (if every price is doubled total costs must double) and it must satisfy conditions corresponding to those of a well behaved production function. At the same time it is highly desirable to be able to analyze fuel choice separately from the choice of labor and capital, particularly when data are scarce. To this end it is assumed firstly that the fuels are a separable and homogeneous physical energy aggregate (E) which allows the cost function to be written (see Fuss [1977] for more detail):

$$C = C(P_K, P_L, H(P_C, P_G, P_O), t, Q) \qquad (2)$$

$$= C(P_K, P_L, P_E, t, Q) \qquad (3)$$

$$P_E = H(P_C, P_G, P_O) \qquad (4)$$

in which P_E is the price of the energy aggregate. This assumption in fact postulates that there are two sub- models - one in which fuel inputs are determined and a second in which capital, labor and energy are determined. The conditions required for separability are that the cost shares of any two fuels are independent of non-fuel prices. This is a critical assumption in that it implies that capital costs of the fuel burning technology do not affect fuel choice. Griffin defended this assumption noting that, at the time, the capital costs of coal fired plants did not exceed those for a gas fired plant by more than 25%. In the last decade capital costs have certainly changed and this assumption must be regarded as requiring investigation before it is accepted unconditionally. The most appropriate place for its application would be in multi-firing where no change in capital is required to switch fuel.

Many studies, as pointed out, have concentrated on estimating the equivalent of (4) - which explains the use of fuels within total energy. Here the desire is for a functional form of the cost function which places few restrictions on the range of response. Griffin, following Christensen, Jorgenson and Lau [1973], uses the translog cost function (this gives different results from a model starting with a translog production function). The translog function is one possible second order approximation to an arbitrary twice differentiable cost function. The basic form is:

$$H = \ln a_o + \sum_i a_i \ln P_i + \tfrac{1}{2} \sum_i \sum_j a_{ij} \ln P_i \ln P_j \qquad (5)$$

where i and j stand for the fuels C, O and G, and a_o, a_i and a_{ij} are parameters to be estimated. Assuming firms are cost minimizing and that there is no monopoly power in fuel markets (fuel prices are exogenous to the industry) equations for fuel cost shares can be derived:

$$S_c = P_c Q_c / P_E E = a_c + \sum_j a_{cj} \ln P_j$$

$$S_G = P_G Q_G / P_E E = a_G + \sum_j a_{Gj} \ln P_j \qquad (6)$$

$$S_O = P_O Q_o / P_E E = a_E + \sum_j a_{Ej} \ln P_j$$

$$(j = C, G, O)$$

The cost shares automatically must sum to unity and this implies the following parameter restrictions:

$$a_C + a_G + a_E = 1 \qquad (7)$$

$$a_{CC} + a_{GC} + a_{OC} = 0$$

$$a_{CG} + a_{GG} + a_{OG} = 0 \qquad (8)$$

$$a_{CO} + a_{GO} + a_{OO} = 0$$

while symmetry in the cost function implies that

$$a_{ij} = a_{ji} \qquad (i,j = C, G, O) \qquad (9)$$

Restrictions (8) and (9) together imply that the translog function is linearly homogeneous, as is required if it is to represent a cost function. These restrictions can be substituted into the fuel expenditure share equations to give the two independent equations:

$$S_C = a_C + a_{CC} (\ln P_c - \ln P_O) + a_{CG} (\ln P_G - \ln P_O) + U_C \qquad (10)$$

$$S_G = a_G + a_{CG} (\ln P_C - \ln P_O) + a_{GG} (\ln P_G - \ln P_O) + U_G$$

where U_C and U_G are error terms. The third equation, for the share of oil, can be entirely predicted from the other two since the shares must add to unity. These equations, which require data on the prices of the fuels and on the share of expenditure on each fuel in total expenditure on energy, need to be estimated jointly by a full information maximum likelihood procedure. This is to ensure that the parameter common to both equations (a_{CG}) is the same in both cases. In addition, if there is contemporaneous correlation between the error terms so that $E(U_C U_G) \neq 0$, improved efficiency can be obtained by the use of a Zellner type estimator. The other parameters from the system (6) can be recovered by using the identities (7) and (8) together with the estimated parameters from (10) - standard errors can be easily computed since the derived parameters are linear functions of the estimated parameters. The own (e_{ii}) and cross price (e_{ij}) partial (i.e. holding total energy constant) elasticities can then be derived:

$$e_{ij} = (a_{ij} + S_i S_j)/(S_i) \qquad (11)$$

$$e_{ii} = (a_{ii} + S_i^2 - S_i)/S_i \qquad (12)$$

where e_{ij} is the percentage change in the quantity of fuel i used caused by a 1% change in the price of fuel j. To calculate these values of the shares (S_i) are required - conventionally the mean sample shares are used. Standard errors for these shares are more difficult to obtain. Possible solutions are discussed by Pindyck [1979] and Berndt [1991]. The system of fuel share equations allows only for substitution between fuels but not for the additional effects that a change in the general energy price will have upon the total amount of energy used. Hence to obtain a <u>total</u> price elasticity (e_{ij}*) (i.e. holding output constant) an adjustment is required as explained by Pindyck [1979]

$$e_{ij}^* = e_{ij} + e_{EE}S_j \qquad (13)$$

where e_{EE} is the own price elasticity of aggregate energy in the total cost function.

Since the translog function is an approximation device it is not automatically consistent with all of the theoretical properties that an aggregate cost function would have. It has already been pointed out that the required properties of linear homogeneity and symmetry can easily be imposed on the estimation equations. However two other properties have given more problems for empirical work. It is necessary that the estimated cost function should be monotonically increasing and strictly quasi-concave in input prices. The former requires that the fitted shares should all be positive at every data point while the latter requires that the matrix of substitution elasticities be negative semi-definite at each observation. The former is checked by using the estimated coefficients in (10) and the actual prices to show that the estimated shares are all positive. The substitution elasticities (Hick-Allen form) are given by

$$\sigma_{ij} = e_{ij}/S_j \qquad (14)$$

For a three fuel model the negative semi-definite property required for strict quasi-concavity requires that

(i) each σ_{ii} 0 at each observation:

(ii) each submatrix: $\begin{matrix} \sigma_{ii} & \sigma_{ij} \\ \sigma_{ji} & \sigma_{jj} \end{matrix}$
($i \neq j$)

has a positive determinant at each observation:

(iii) the matrix

$$\begin{matrix} \sigma_{ii} & \sigma_{ij} & \sigma_{jk} \\ \sigma_{ij} & \sigma_{jj} & \sigma_{jk} \\ \sigma_{ik} & \sigma_{jk} & \sigma_{kk} \end{matrix}$$

has a zero determinant at every observation (this may be near to zero reflecting rounding error in the computations).

The third condition is purely a check on the correctness of calculations but the violation of either of the other conditions implies that the fitted model is not consistent with a genuine cost function.

It can be seen that estimation of the fuel share equations does not allow all the parameters of the total translog function for energy (5) to be derived - here the parameter a_0 is not estimated.

Some of the restrictions on the model required by theory can be tested formally. For example symmetry can be tested by estimating the fuel share equations with or without the imposition of the symmetry conditions. The two likelihood scores can be compared by the standard likelihood ratio test:

$$LR = -2(\ln L_0 - \ln L_1) \tag{15}$$

where L_0 is the constrained and L_1 the unconstrained value of the likelihood statistic given by the computer output. The LR statistic has a chi square distribution, with degrees of freedom equal to the number of restrictions imposed, if the null hypothesis of symmetry is correct.

Although much early work on fuel shares was based on the translog approximation to the cost function there have been recently attempts to find alternative and superior models for estimating fuel substitutability. The original reason for the enthusiasm for the translog was that the elasticities of substitution between factors were not over-restricted. The definition of an elasticity of substitution - the percentage change in the ratio of two inputs caused by a one percent change in the price ratio of the inputs shows that they describe the degree of curvature of the isoquants. Cobb-Douglas type functions have all elasticities equal to unity while the C.E.S. function of Arrow et al.

[1961] has all elasticities constant. The translog function instead has elasticities which vary depending on the fuel shares and which thus allow a more flexible description of the relation between the various inputs. It is important to recognize that in the translog approach the elasticities must vary if the fuel shares vary, as (11) indicates. Constancy is not a testable assumption. Other general approximation systems that have been suggested for similar inter factor substitution are discussed by Berndt. They include the generalized Leontief cost function:

$$C = Q\left[\sum_i\sum d_{ij}(P_iP_j)^{1/2}\right] \qquad (16)$$

hich yields input/output demand equations which are functions of the price ratios. The cross price elasticities are given by:

$$e_{ij} = d_{ij}\ (P_i/P_j)^{-1/2}/2a_i \qquad (17)$$

where a_i is the ratio of the quantity of input i to total output. Variations on the translog form which include an allowance for technical progress on all factors are also discussed by Berndt.

Considine [1989] has pointed to some of the weaknesses of the translog function in proposing a linear logistic alternative model for fuel shares. He shows that for empirical problems where there are limited substitution possibilities, a small cost share for one or more inputs and a high variance in relative prices, the translog performs badly in that concavity is not satisfied at all data points. It would be possible to use generalized cost functions in which global concavity can be imposed as in Diewert and Wales [1987] but these require many more parameters and hence more data. Instead Considine suggests a model in which concavity holds automatically but in which symmetry holds only in a limited region. He suggests that this trade off may be preferable since wrong signs on own price elasticities and predictions of negative fuel shares are unhelpful for policy analysis. The fuel shares (S_i) instead of being linear as in (6) are postulated to be of the form

$$S_i = \exp\{f_i\}/\sum_i \exp\{f_i\} \qquad (18)$$

where

$$f_i = d_i + \sum_j d_{ij} \ln P_j \tag{19}$$

This is a linear logit (or logistic) model of cost shares. It should be noted that it is not related to logit models of discrete choice. The share elasticities are:

$$H_{ik} = d_{ik} - \sum_j S_j d_{jk} \tag{20}$$

and the own and cross price (partial) price elasticities

are
$$E_{ij} = H_{ij} + S_j \tag{21}$$

$$E_{ii} = H_{ii} + S_i - 1 \tag{22}$$

Certain conditions have to be imposed in order for these equations to be consistent with theory as is shown by Considine and Mount (1984). Homogeneity of the cost function with respect to prices can be imposed by the restrictions:

$$\sum_j d_{ij} = d \qquad \text{all } i \tag{23}$$

where d is an unknown scalar that can be set equal to zero. Symmetry can be imposed by the constraint

$$d_{ij}^* = d_{ji}^* \qquad \text{all } i \neq j \tag{24}$$

where

$$d_{ij}^* = d_{ij}/S_i^* \tag{25}$$

and S_j^* is the mean cost share for fuel i.

It can be shown that for two inputs the logit cost share model collapses to a constant elasticity (CES)
model. The estimating equations for the three fuel case can be written:

$$\ln(S_1/S_3) = (d_1 - d_3) - [S_2^* d_{12}^* + (S_1^* + S_3^*)d_{13}^*] \ln(P_1/P_3)$$
$$+ [d_{12}^* - d_{23}^*]S_2^* \ln (P_2/P_3) \tag{26}$$

$$\ln(S_2/S_3) = (d_2 - d_3) - [S_1^* d_{12}^* + (S_2^* + S_3^*)d_{23}^*]\ln(P_2/P_3)$$
$$+ (d_{12}^* - d_{13}^*)S_1^* \ln (P_1/P_3) \tag{27}$$

These equations can be estimated by full information maximum likelihood using price ratios and expenditure shares. Parameters can be recovered using mean shares. Considine shows that, for a set of fuel shares for U.S. industry data, a translog model fails concavity for 6 observations while the logistic does not fail once. More importantly the own price elasticities from the translog vary greatly from observation to observation, while for the logistic they are nearly constant.

In a search for other functional forms Mountain and Hsiao [1989] have made some further suggestions. For a three input model they firstly look at a Quadratic quasi Cobb-Douglas (QQCD) form in which the relative inputs are related to prices by:

$$\begin{aligned}\ln(X_2/X_1) = {} & a_2 + a_{22}\ln(P_2/P_1) + a_{23}\ln(P_3/P_1) \\ & + \tfrac{1}{2}a_{222}[\ln(P_2/P_1)]^2 \\ & + a_{223}\ln(P_2/P_1)\ln(P_3/P_1) \\ & + \tfrac{1}{2}a_{233}[\ln(P_3/P_1)]^2 \end{aligned} \tag{28}$$

$$\begin{aligned}\ln(X_3/X_1) = {} & a_3 + a_{32}\ln(P_2/P_1) + a_{33}\ln(P_3/P_1) \\ & + \tfrac{1}{2}a_{322}[\ln(P_2/P_1]^2 \\ & + a_{323}\ln(P_2/P_1)\ln(P_3/P_1) \\ & + \tfrac{1}{2}a_{333}[\ln(P_3/P_1)]^2 \end{aligned} \tag{29}$$

As an alternative to this form they propose a Fournier based approximation for the expenditure shares:

$$\begin{aligned}S_i = {} & a_i + \sum_{j=2}^{3} a_{ij}\ln(P_j/P_1) - 2\{d_{12}\sin[\ln(P_i/P_1)] \\ & + d_{13}\sin[\ln(P_2/P_3)] + e_{12}\cos[\ln(P_i/P_1)] \\ & + e_{13}\cos[\ln(P_2/P_3)]\} \end{aligned} \tag{30}$$

For this to be consistent with a cost function the following restrictions must hold:

$$d_{23} = -d_{33},\ e_{23} = -e_{33},\ a_{23} = a_{32} \tag{31}$$

Both models are applied to fuel choice for individual industries in Canada. Both produce good results in some cases. An important aspect of their models is the introduction of technical progress. Further investigation of these systems is given by Mountain, Stipdonk and Warren [1989].

A different approach to estimating elasticities of substitution is to use the production function rather than a cost function. The main issues have been described by Burgess [1975]. For Cobb-Douglas and C.E.S. models the production and cost functions are self dual so that the approaches are equivalent. However for the more flexible translog functions the two forms are not self dual so that the elasticities derived will in general be different and so inferences based on the two approaches will be different. If output can be represented by a function quadratic in the logarithms of inputs (measured in physical units) then, with efficient production and competitive factor markets, the cost share equations are linear in the logarithms of factor quantities (as opposed to factor prices for the log quadratic cost function):

$$S_i = \beta_i + \sum_j \gamma_{ij} \ln X_j \tag{32}$$

with parameter restrictions

$$\sum_i \beta_i = 1; \sum_i \gamma_{ij} = 0 \text{ (all} j) \tag{33}$$

The factor share equations require data on prices and quantities, which is also needed for the cost share approach, so that the data requirements are equivalent in the basic case. Burgess estimates a time series model by both approaches and shows that the estimates of the elasticities of substitution (year by year) are quite different in some cases - indeed they are of different sign on occasion. This result, which is based on different approximations to a 'true' underlying cost function, is used by Burgess to suggest that care must be taken before accepting the values derived from any one approach. A further point to notice is that it is usually assumed (for econometric purposes) that quantities are exogenous in (33) while prices are exogenous in the cost function approach. Depending on the nature of the economy one or other assumption may be more realistic. In general the prices of traded fuels (oil and perhaps coal) are likely to be exogenous to the sectors being estimated. Finally, if a fuel is not used then the presence of the log of quantity term rules out the use of including that fuel in the model (as in a cross section where some firms or countries do use the fuel in question).

This brief review of the various econometric models used for analyzing fuel shares and fuel substitution highlights several practical issues:

(i) Although most models appear to fit well on superficial criteria (e.g. goodness of fit), more extensive testing for concavity and the stability of price elasticities at various data points can lead to unsatisfactory performance.

(ii) No one model appears to be best in all cases. Different models may be needed for different circumstances.

(iii) Care needs to be taken over the definition and measurement of the competing fuels in specific industries. For example, in power generation the fuel used is heavy fuel oil, so that the price used should not be that of petroleum products as a whole (the price of gasoline can move quite differently from that of HFO).

(iv) All the models proposed require estimation by full information maximum likelihood techniques. This can be handled by standard software packages (such as TSP) but the performance of such techniques with very small sets may not be very reliable.

(v) The use of these econometric models appears to be largely limited to highly developed countries (e.g. the U.S., Canada, Australia). In principle they are applicable in any situation but data limitations are an important consideration. At an industry level it is necessary to have fuel prices and shares in total energy expenditure for a number of years disaggregated by industry type (in order to avoid the effects of the shift in the composition of industry).

(vi) All the models described provide estimates of own and cross price elasticities for the various fuels. These are very important for policy purposes since they indicate the potential response to changes in fuel costs which could be brought about by state intervention. In the light of this it is important to find a model which gives stable values for these elasticities. Merely checking the elasticities at the mean values of historic energy shares is an insufficient check - they need to be evaluated at all data points. The work of Considine is particularly helpful in suggesting an alternative to the translog model which is well known for producing highly variable elasticities.

(vii) Very little work has been undertaken on dynamic models. Since adjustment to fuel price changes may take several years this is an important issue. Cross-section studies are one attempt to pick up the effects of different relative prices without the need to model short term dynamics, but these raise problems of homogeneity (particularly for the industrial sector). The theoretical problems of building a fully specified dynamic model have been discussed by Epstein [1981] and Nakamura [1986]. One major problem would be the requirement for disaggregated information on the capital stock by energy type -which is rarely available. As an alternative Mountain and Hsaio suggest using autoregressive specifications for the fuel share equations to pick up some of the partial adjustment.

Some general conclusions on the suitability of econometric models for measuring the degree of fuel substitutability can be drawn. Econometric models are designed to use published aggregate data to give an estimate of the degree of substitution between fuels that has taken place in response to changes in relative prices, without detailed field work or a case by case approach they provide a measure of such substitutability. This is best seen as a first approximation for the purposes of policy - an indication of where substitution has taken place and hence of the potential for further change. The extrapolation of results from one study to other cases appears at this stage of knowledge to be limited to suggesting which industries or circumstances are worth more detailed investigation. As the study by Mountain and Hsaio indicates there is not yet strong agreement from different researchers on price elasticities even when they are all analyzing the same data (e.g. specific industry values in Canada). Different methodologies yield very different elasticities and would result in very different strengths of policy recommended to achieve the same degree of fuel switching. Comparing results between countries is even less satisfactory. Here there is substantial dissatisfaction over model choice, with some models on occasion producing counter-intuitive results (the wrong sign for own price elasticities etc.). The extrapolation of estimates from such models to countries with completely different industrial structures and technologies is not likely to be reliable.

The Engineering Approach

The engineering approach to fuel substitution has generally been at a plant specific level, although some recent studies here attempted to draw more general lessons on the preferred technology (see Moore and Crousillat [1991] and Pinto and Besant-Jones [1989]).

The key difference in engineering studies is that a specific situation is analyzed and this involves an analysis of all the costs of alternative proposals. Such costs involve capital and infrastructure costs as well as fuel costs and are technology specific. It is necessary to specify fully what change is being proposed and what are the existing conditions. Three examples illustrate the nature of the difference from the econometric approach.

(i) A country may possess already a multi-fired power station - one capable of burning different fuels. The issue is simply which fuel to burn. This will depend on fuel costs at the burner tip and on the thermal efficiency of the different fuels - the various forms of solid fuel have a wide range of thermal output per unit weight. If the power station is already in place there are no direct capital costs of switching but there may be infrastructure costs to be incurred if a switch in fuel is required. The price of the fuel must include all the transport costs of getting it to the power station (simple border prices for imported fuels would not be correct). This example, which is nearest to the putty-putty approach implicit in much econometric work, demands the least data. Where all capital costs are already incurred then the relative fuel prices at which substitution would occur can be simply calculated. The pollution characteristics can also be easily identified, unlike the econometric case where there is no data available at the level of aggregation used.

(ii) A country has an existing coal (say) thermal power unit and is considering conversion to a gas fired combined cycle plant. This ex post substitution includes a crucial asymmetry in that the capital costs for one scheme have already been incurred. Any new scheme would require large capital costs in addition - the scrap value of existing plant and its expected life before replacement would be crucial information in any cost benefit analysis. In addition the thermal efficiency and pollution characteristics of both plants would play an important part in deciding whether the switch were worthwhile. Often it turns out to be best to technically upgrade a poor plant than to entirely replace it. Econometric models do not attempt to ask such questions and hence cannot be expected to provide the appropriate solutions.

(iii) In the case where an increase in generating capacity is being contemplated there is genuine ex ante substitutability between fuels - the issue is then which fuel and which technology would be best. In practice a key issue, particularly when pollution is a concern, is the location of the plant. This affects total costs depending on the accessibility of the various fuels and the infrastructure available. Again econometric modelling can at best hope to provide only an average picture for a very specific problem.

The strength and potential accuracy of the engineering method, which is discussed in more detail below, is that it takes full account of the conditions under which a fuel switch may take place. Because this is typically plant specific it may be that no general lessons can be learned. A fuel tax that is predicted to be effective in leading to fuel switching at a specific site cannot have its impact generalized to other sites without a detailed examination of every case.

The simple level of engineering related fuel choice is that which focussed solely on the characteristics of the plant itself, while the more detailed study looks at the whole context in which a fuel choice is to be made. Examples of both approaches are discussed in some detail since they illustrate both how the approach is used and its strengths and weaknesses.

Non Site Specific Choice of Power Generation Technology

Many studies of the power market attempt to compare different fuels together with the different technologies available in order to make predictions about future fuel use. One very recent study by Moore and Crousillat [1991] looks at the prospects for gas-fueled combined cycle power generation with specific reference to its future use in developing countries. The conclusions to the study indicate the attempt to draw general conclusions. The advantages are claimed to be:

(a) a lower capital cost of about \$600/kw compared to steam thermal at \$800-1500/kw, depending on whether it is conventional (coal or oil) steam of coal fluidized bed and on the degree of stack emission control equipment;

(b) thermal efficiency of about 50% compared to 40% or less for the alternatives;

(c) better environmental performance;

(d) shorter construction time;

(e) shorter startup and loading times.

The disadvantages are:

(a) the limited fuel-switching capability compared to a conventional steam unit, which can be designed for gas, oil and coal firing;

(b) poor operating performance so far in developing countries largely associated with inadequate preparation for the transfer of the high technology system.

In addition it was shown that for under sensitivity analysis the gas fueled combined cycle plant was least cost over a wide range of situations.

The study takes 1994 as its commissioning date for new plant and considers base load systems with gas combined cycle or coal or oil alternatives for both large (5000 MW) and small (1000 MW) installed capacity systems. It does not make allowance for high altitude or high ambient temperature, both of which affect gas turbine efficiency adversely. The assumptions are worth reporting in detail since they illustrate how much information is required - Table 3.1 gives the comparative values for large power systems:

Table 3.1 : Comparative Assessment of Generation Costs for Large Power Systems

	Combined Cycle Gas	Coal Fired Steam	Fuel-oil Fired Steam
Capacity (MW)	450	500	500
Plant factor (%)	65	65	65
Energy Supply (Gwh)	2562	2847	2847
Unit Cost ($/kw)	600	1000	900
Total investment cost (Million $)	310	575	518
O and M Unit cost (¢/kwh)	0.5	0.5	0.3
Heat content (BTU/unit)	1	25	5.9
Thermal efficiency (%)	46	38	39
Fuel price ($/unit)	2.5	40.0	15.0
Fuel price rise (%/year)	1.0	1.0	1.0
Annual fuel cost (Million $)	47.5	40.9	63.3
Implementation period (years)	3	5	5
Economic Life (years)	20	25	25
Generation cost (¢/kwh)	4.2	4.9	5.5
Discount rate (%)	10.0	10.0	10.0

(No allowance has been made for flue gas desulfurization units for coal burning.)

Source: Moore and Crousillat [1991]

The assumptions for the relative fuel prices and thermal efficiencies are particularly important. The sensitivity analysis showed that under almost all circumstances the combined cycle plants would be least cost. Oil fired were not economic at prices even as low as $10/barrel for oil ($20 was taken to be the constant oil price in the base case). Coal firing became competitive for gas prices of $3.3/MMBTU (base case $2.5) or coal prices of $20/ton (base case $40/ton). A rise in capital costs of gas of 10% and gas prices of $3.0 also favored coal. The critical parameter, given the experience of combined cycle in developing countries, is the plant factor. If this were about 15% points lower than for coal at 50% then gas ceases to be the least cost fuel. A similar analysis was carried out for smaller systems and again showed gas combined cycle to be the least cost option.

The methodology adopted in this study is that of identifying current good practice technologies and their actual operating characteristics (rather than theoretical optima) and using known cost data to compare the discounted costs per unit of generating a certain amount of energy over the life time of the plant. Similar technical data can be provided for the emissions of each type of fuel/plant per kwh as is shown in table 3.2 reprinted by Moore and Croussillat:

Table 3.2: Comparative Emissions for Gas Combined Cycle and Coal Steam Plant per kwh

	Coal Steam with Scrubber	Gas-fueled Combined Cycle
CO_2, grams	830	380
CO, mg	75	34
SO_2, mg	600	0
NO_2, orig	600	350
UHC, mg	0	18
Waste water, grams	15	0
Ash, grams	34	0
Rejected heat, MJ	4.3	2.6

Source: Haupt, Joyce and Kuenstle [1990].

The detail of the sensitivity analysis and of the potential for a precise evaluation of the pollution characteristics of particular technologies cannot be matched by econometric analysis because of its essentially aggregate nature. The broad implications of studies such as this, which are reflected in other comparative technology studies, give some hope of reaching sufficiently broad conclusions that national policy can be rested on them.

<u>Site Specific Choice of Power Generation Technol</u>

The previous study is applicable in the general case only when the assumptions hold true at every site. In particular it requires every site to be 'greenfield', that fuel prices are always identical and there are no associated infrastructure costs involved in using any of the fuels. More specific analysis will pay attention to these factors, but the results (as opposed to the methodology) cannot then be so easily generalized.

An example of the methodology required to assess fuel substitutability in a specific situation is provided by Pinto and Besant-Jones [1989] for power generation. Although the case they examine is hypothetical it is elaborated in sufficient detail to show how it could be applied in actual cases. The objective is to ascertain the demand curve for gas in three different power systems (i.e. the relation between the price of gas and the amount of gas used and the mix of the generation system). The three systems were chosen to illustrate realistic situations.

> <u>System A</u> is small with a current maximum demand of 100 MW. The load factor is assumed constant over the 20 year period at 54.5%. The initial power system is entirely thermal with no possibility of future hydro and there is no possibility of importing coal due to the high costs of coal handling plant. The inherited plant mix is five 33 MW steam units fired by residual fuel oil and some diesel units. The steam units are new and not retired over the simulation period, whereas the diesels are retired between 6 and 14 years in the future. The rate of load growth is 7%.
>
> <u>System B</u> has a current maximum demand of 2400 MW with a higher load factor of 69.7%. At present it has a varied plant mix with hydro/storage, lignite fired steam, gas turbines and diesel. All of the inherited plant is retired over the period. Again load growth is 7% per annum.
>
> <u>System C</u> is a 'greenfield' case with an initial maximum of 800 MW. There is no possible hydro source.

For the thermal plants the following details are used:

(i) Nameplate rating

(ii) Sent out rating

(iii) Maximum availability

(iv) Full load heat rate

(v) Average heat rate

(vi) Variable operation and maintenance costs

(vii) Fixed staffing costs

(viii) Capital costs phased over the construction period

(ix) Economic life.

An important set of variables are the fuel prices. These are assumed to escalate in real terms over the period, but gas prices were assumed constant in real terms. For coal it is assumed that transport costs were 29% of the fob price for the system B case. For distillate the transport cost was 4% of the fob price. An important set of costs are those for conversion to gas firing - allowance is made for the fact that in system A only the oil fired steam units are capable of conversion and that this is expensive because they were not designed with this in mind.

The overall system was optimized in each case to determine the least cost development program. Because of the complexities of the analysis only a limited range of unit sizes of each type of plant was considered (gas turbines, combined cycle and steam units). The optimization of a complete power system is a much more complex operation than the choice of a least cost plant to generate a certain amount of energy, as is explained in book on power system economics by Berrie [1983]. Peak demand is a particularly important phenomenon as well as unpredictability of demand. The former requires some capacity that can easily be switched in and out but which is not used all the time. The latter requires some reserve over expected demand. A merit ordering of power plants exists at any moment in which extra capacity is switched on to meet the temporary increments in demand. The economic characteristics of base load and peak load plants can be quite different. A second issue in optimizing a development plan is its dynamic nature - decisions which are best for today may not be best for five years' time, but once taken are very expensive to undo through conversion etc. A series of alternative development plans is evaluated at six different prices for gas (from $1/MMBTU to $6/MMBTU) and in each case the least cost is identified. This then gives figures for the amount of gas used and the amount of investment as the price of gas is varied. For example in system A when the gas price is in the range up to $2/MMBTU the least cost program is to use only gas turbine plants by conversion of steam units to gas firing in the early years of the program. As the price increases to $3/MMBTU the improved efficiency of combined cycle becomes important. Above $3.17 conversion of steam plant to gas firing is no longer economic. Above $4/MMBTU there is no demand for gas until 1988 when additional fuel efficient combined cycle plant is commissioned. The demand curve shows rather strong discontinuities in fuel switching with the location of the switch points determined by all the characteristics of the system. Similar analysis is carried out for systems B and C.

This approach is clearly site specific in the cost structure of the power plant. In addition, were this approach to be carried out for specific sites there would be differences in fuel costs due to the transportation cost element (or quality element, especially for coal), local operating cost differences etc. No two sites are necessarily the same, which reinforces the conclusion that the switch point prices are site specific.

The general conclusions of the report are worth stating in full:

"(i) For all power systems there is a price of gas below which demand is relatively inelastic. This value is a function of system specific variables such as the available fuels, the mix of generating plant etc. In the case of a relatively small system ... with no provision for coal burning and no hydro capacity, gas demand is not sensitive to price reductions below $3/MMBTU. For a much larger system ... with a mix of generating plant including hydro with storage, coal and lignite burning steam, and gas turbines, the critical price of gas is approximately $2/MMBTU. For an intermediate size system with ... a full range of available fuel types, and no constraint on inherited plant mix, the critical price of gas is approximately $3/MMBTU.

(ii) As the price of gas varies, the demand for gas does not change at a constant rate, but rather moves through a series of discontinuities. Sharp increases in gas demand result from the commissioning of new gas fired generation plant, and decreases can be the result of changes in merit order of gas fired plant relative to other plant.

(iii) The discontinuities in the gas price/demand relationships occur at prices which represent switches between investment and operating decisions, for example from gas fired steam units to coal fired steam units. These prices depend upon a number of factors, the most important of which are expected fuel prices and the relative costs of different types of new generating plants.

(iv) The precise shape of a demand curve is dictated both by the critical prices of gas which are important in determining the optimal plant mix (the investment decision) and by changes which alter the merit order ranking of plant. It is thus system specific. Where the latter is important the demand curve usually assumes the conventional shape of having a negative slope with respect to the price axis."

The general shape of the demand curve is of considerable interest, given that econometric studies are an attempt to approximate it. Whereas the econometric model shows a continuous and declining rate of substitution between two fuels, leading to a downward and smooth (partial) demand curve for a single fuel, the engineering approach shows a downward curve made up of a series of steps - each step corresponds to a switch to a different technology and its associated fuel. The width of the steps depends on the system characteristics.

Although there are a number of studies which analyze fuel choice in power generation from an engineering/least cost approach there is not the same interest in industrial processes. Of course individual firms carry out such analysis but little is said in general terms. This is because industries are so product specific that the nature of the energy requirements tends to be very specific. However there are virtually no problems of system optimization and the choice is able to be made on the characteristics of individual energy using plants. The same principles apply as in the first example for power - it is crucial to know the output required, the capital costs of competing plants, the costs of competing fuels at the burner tip, the efficiency of various technologies in the specific use, the pollution characteristics of the various choices etc.

A study by Fog and Nadkarni [1983] analyses possibilities of fuel substitution for the cement industry. In particular they consider the economics of switching from the use of fuel oil to coal. Not only are the direct fuel costs compared but also the capital costs associated with the conversion. Not only does the coal have to be specially prepared (ground and dried) prior to loading into the kiln but facilities for homogenizing the calorific value of the coal have to be constructed. Finally transport costs for the associated infrastructure (depending on the existing facilities) must be added. Rates of return on oil to coal conversions are calculated for various oil/coal cost differentials and kiln sizes. The detail of this study, which takes into account the specific technology and costs of a particular industrial process confirms that in order to apply the methodology of identifying "switch" points it is necessary to have detailed information on the configurations and costs of all existing plants within an industry.

A Comparison of the Econometric and Engineering Approaches to Measuring Fuel Substitutability

The purpose of this paper is to evaluate the use of various approaches to measuring the potential for fuel substitution in response to price related market instruments with a view to attaining a lower level of pollution from the encouraged fuel. It is therefore necessary to be able to assess the degree of fuel substitutability brought about by a given price change and the associated change in pollution.

The econometric approach typically takes economy wide data on power, aggregate industry or particular industries and establishes the degree to which aggregate fuel substitution in the past is associated with price changes of the different fuels. The data requirements are several years' information on the prices and volumes of the different fuels used. For more sophisticated models, in which allowance is made for changes in the total demand for energy brought about by the impact of individual fuel prices on the aggregate price of energy, it is necessary to have information on the price and volume of capital and labor used. For developed countries such data are readily available, at least for industry as a whole and for the power sector. For developing countries the data is often likely to be less comprehensive.

The key assumptions for econometric models are that all fuels are used (or at least all of a subset are always used) and that there is continuous substitutability between fuels in response to fuel price changes. Models of fuel shares also ignore capital costs of fuel switching or assume that all technologies cost the same. This latter assumption fails to distinguish between ex ante and ex post substitution - the former requires completely new plant whichever fuel is chosen, while the latter may require no new plant (multi-firing) or require expenditure on conversion if the fuel mix is to be changed. The assumption of continuous substitution is particularly restrictive since no one plant is likely to use a mixture of fuels in the way that it uses a mixture of labor, capital and energy. Rather there is a preferred fuel/technology which will be switched at a certain value of the price ratio. Only if there are many plants, each with slightly different values for the switch point (caused by differences in local fuel prices, age of capital etc.), will the aggregate behave as if there were a single plant with continuous fuel substitutability. In order for there to be a decreasing rate of substitution, as implied by the traditional cost function, the distribution of switch points would need to follow an extremely limiting and unlikely pattern. However, if plants have idle capacity, then there is a possibility of continuous substitution until full capacity is reached as pointed out by Johansen [1972]. For industries with many small plants the econometric model may be a reasonable approximation to the actual possibilities but it is very unlikely for it to be close for power systems. In addition the published data for power systems in developing countries suggest that often only one or perhaps two fuels are presently used, while policy may be to encourage the choice of another fuel with better pollution characteristics. Econometric models for such a country could give no guide as to the price at which this might happen, since the fuel in question could not be included in historical substitution analysis.

By the nature of the aggregate data used econometric models must use average emission rates for the various fuels - they cannot be technology specific.

Engineering studies attempt to evaluate specific situations in which one fuel may be substituted for another and by taking all costs and technical information into account to reach an accurate picture of the sensitivity of fuel choice to the price of that fuel, as well as to other variables. In power generation this calculation is certainly system specific so that the installed technology plays an important role in determining fuel choice. Capital costs and technological characteristics are also key variables in the analysis. The specificity of the technologies chosen also allow a precise evaluation of the pollution characteristics of the plant or system.

The data required for engineering analysis at a plant level are those which a firm would take into account - capital costs of alternative technologies, likely fuel prices, technical performance, likely demand growth etc. For the government it is likely that such data would be available economy wide for the power sector, since this is often state controlled. Whatever the form of ownership, the management will optimize over its system as a whole when taking investment/fuel choice decisions.

For industry the information required for government intervention to affect fuel choice is much more diverse and very unlikely to be available for the economy as a whole. It would be necessary to have data on existing technology by capacity and performance as well as plant specific fuel prices for every plant in the economy. For a given industry if it were narrowly enough defined the range of potential technologies and costs could be assembled but where a large number of plants were in operation, the necessity to make a separate evaluation of the price at which fuel switching would take place would be very demanding.

In summary it appears that engineering studies are likely to be much more reliable in producing a plant level analysis of the sensitivity of fuel choice to prices. Econometric studies cannot be expected to give accurate answers, but because of the lesser level of demand for data, may be able to provide some guidance to the order of magnitude of response that may be produced. There is an apparent distinction between power systems and industry analysis. The former is homogeneous in terms of the technologies used (all sites face the same choices) and is often owned and optimized by a single authority. The data for an engineering approach is likely to be available and certainly should be utilized if possible. Even a plant by plant analysis (ignoring system inter-relationships) is likely to be a more trustworthy guide than econometric analysis. Industry analysis may have to be carried out by econometric techniques because of lack of information, unless the study is to be confined to a few large scale plants which dominate the sector.

4. EVIDENCE ON FUEL SWITCHING ELASTICITIES

Econometric modelling produces estimates of own price and cross price elasticities which are based on country and industry level data. They represent average responses over time and over all the various plants in the aggregate. Values of these elasticities could be used for the countries concerned to simulate the effects of pollution taxes. If it were found that such elasticities have a general pattern then this may be able to provide some guidelines for the analysis of other countries outside the sample. Although the sector which is best suited to econometric analysis is power generation, because of the product homogeneity, the larger emphasis has been on measuring substitutability in industry. The level of aggregation for the latter is an important factor in determining the extent to which results can be generalized to other situations.

Elasticities in the Electrical Power Generation Sector

Griffin [1977] refers to earlier studies which estimated inter fuel substitution elasticities for the electricity sector. These were for single countries. Griffin's study has the great advantage in that it pooled cross-sections and time series data which allowed for differences in elasticities between countries. Data was for twenty O.E.C.D. countries measured at four five year intervals (1955 to 1969). His basic model hypothesized only inter country variations in relative prices were important. This was on the basis that long standing inter-country differentials in fuel prices accounted for fuel input choices in a long run equilibrium content. Hydro and nuclear sources of electricity were excluded. The model, as explained in section 3, was a translog cost function in which fuel shares are determined independently of the share of energy in total factor input. The estimated model imposes both the equality (linear homogeneity) and symmetry restrictions and the assumption of concavity was checked at every data point and found to be satisfied. The own and cross price elasticities at mean fuel shares for each country are calculated. Table 4.1 reports the own price elasticities between fuels, ignoring the general substitution between energy and other factor inputs. The key point to notice is that the differences in elasticities do not come from attaching separate parameters to each country (only a single set are used) but from the evaluation of the elasticities at the different shares. If two countries had the same fuel shares then they would have the same elasticities.

Table 4.1: Griffin's Estimates of Own Price Elasticities in the Electricity Sector

	Coal	Gas	Fuel Oil
Canada	-0.66	-0.95	-2.94
U.S.A.	-0.66	-0.90	-3.46
Japan	-0.55	-2.40	-1.83
Austria	-0.79	-0.79	-3.22
Belgium	-0.75	-0.83	-3.08
Denmark	-0.51	-	-1.79
Finland	-0.86	-0.91	-1.99
France	-0.74	-0.80	-3.65
West Germany	0.39	-1.14	-10.25
Greece	-0.93	-	-0.98
Ireland	-1.16	-	-0.78
Italy	1.01	-1.17	-1.26
Netherlands	0.48	-1.65	-2.37
Norway	-3.90	-	-0.40
Portugal	-0.89	-1.42	-1.27
Spain	-0.44	-2.12	-2.45
Sweden	-2.36	-4.12	-0.49
Switzerland	-	-	-0.34
Turkey	-0.69	-1.23	-1.85
U.K.	-0.35	-1.82	-3.74
O.E.C.D.	-0.57	-0.94	-3.12

(Blanks indicate that a given country does not use the fuel for electricity generation.)

Griffin noted that the own price elasticities are considerably higher than those based just on time series data for the U.S. His own earlier work had found -0.3 for coal, -0.0 for gas and -0.2 for fuel oil, while Hudson and Jorgenson [1974] had found -0.45 for coal, -0.10 for gas and -0.88 for fuel oil. He interpreted the lower values as being short run (perhaps an adjustment period of only 2 years) while the cross section results were nearer to long run values with a 20 year adjustment pattern. Table 4.2 provides the corresponding cross-price elasticities which again differ between countries according to their fuel shares.

Table 4.2: Griffin's Estimates of Cross-Price Elasticities in the Electricity Sector

	Gas/Fuel Oil	Coal/Fuel Oil	Coal/Gas
Canada	0.66	0.53	0.13
U.S.A.	0.53	0.50	0.16
Japan	3.67	0.62	-0.07
Austria	0.50	0.57	0.21
Belgium	0.54	0.56	0.19
Denmark	-	0.61	-
Finland	0.73	0.74	0.12
France	0.49	0.52	0.21
West Germany	0.77	0.30	0.08
Greece	-	1.11	-
Ireland	-	1.41	-
Italy	1.25	1.05	-0.04
Netherlands	1.91	0.51	-0.03
Norway	-	5.52	-
Portugal	1.69	0.96	-0.07
Spain	2.93	0.49	-0.05
Sweden	8.22	3.14	-0.79
Switzerland	-	-	-
Turkey	1.18	0.68	0.01
U.K.	2.18	0.38	-0.03
O.E.C.D.	0.66	0.47	0.11

Although this table also shows substantial variations between countries it does suggest that the degree of substitutability between coal and gas was very low over the period. Griffin attributes this in part to the tendency to use coal for base load and gas for peak load in many countries, and to the empirical fact that few countries have indigenous supplies of both coal and gas (which are much less traded than oil). The Hudson/Jorgenson estimates for the U.S. power sector were for gas/oil at 0.20, coal/oil at 0.43 and coal/gas at -0.20. Again the longer run nature of Griffin's data supports a view of a higher degree of substitutability.

There have been relatively few attempts to measure econometrically the potential for fuel switching in power generation using more recent data. The series of studies published just before and just after Griffin's cross country analysis concentrated largely on problems of disentangling long and short run elasticities. Donelly [1987] estimated values for Australia using slightly later data, but there appears to be no wide ranging study using data covering a substantial period after the second oil shock. Since it is widely agreed that the life of capital in the power sector is of the order of twenty years, it would be desirable to re-estimate Griffin's model using data which covered all of the 1980s. There have been a large number of studies looking at the comparative economics of different fuels for power generation and trying to identify the break even price but either these are hypothetical greenfield studies or else they are situation specific. Few general lessons can be drawn from these studies particularly since the conclusions are always very dependent on the costs and performance of the technology investigated and the price path assumed for the competing fuels. The method is perfectly suitable for application wherever there is data but, by its very nature, the quantitative aspects of the results cannot be generalized.

Elasticities of Fuel Switching in Industry

Unlike the power sector there has been a continuous interest in econometric modelling of fuel choice in the industrial sector. This may be because the issue of fuel choice appears simpler. Power raises the difficulties of dealing with hydro and nuclear and the crucial distinction in many countries between base and peak load firing. Industry appears to use all major fuels, if a high enough degree of aggregation is used, and time series data suggests that considerable inter fuel substitution has taken place over time.

The first oil shock produced considerable interest in measuring inter fuel substitution (away from oil) as well as energy substitution. Pindyck [1979] is a major example of such studies using translog functions and allowing for the total energy substitution against other factors. The model pooled data on ten industrialized countries for the period 1959-1973. The coefficients for the parameter of energy substitution against other factors was allowed to vary between countries, but the parameters for inter fuel substitution were constrained to be equal. As in Griffin's work on power, the evaluation of elasticities of country mean shares for each fuel allows the elasticities of substitution to vary between countries. The results for the aggregate industrial sector are extensive but the key values are the partial fuel price elasticities shown in tables 4.3. and 4.4.

Table 4.3: Pindyck's Partial Own Fuel Price Elasticities for the Industrial Sector

	Coal	Fuel Oil	Gas	Electricity
Canada	-1.80	-0.81	-0.33	-0.14
France	-1.04	-0.20	-1.49	-0.16
Italy	-1.49	-0.29	-1.30	-0.13
Japan	-1.32	-0.20	-1.49	-0.12
Netherlands	-1.67	-0.11	-1.42	-0.07
Norway	-2.08	-0.34	-	-0.08
Sweden	-1.26	-0.27	-	-0.12
U.K.	-1.12	-0.22	-1.38	-0.15
U.S.A.	-2.17	-1.10	-0.52	-0.08
West Germany	-1.09	0.03	-2.31	-0.12

The own price elasticity for electricity is uniformly low and that for oil is surprisingly low, but this may well reflect the fact that the data does not include the oil shock periods. The model did not impose symmetry so for each pair of fuels there are two elasticities of substitution. The values are not very different so just one set is presented.

Table 4.4: Pindyck's Cross Price Partial Fuel Elasticities for the Industrial Sector

	C/O	C/G	C/E	O/G	O/E	G/E
Canada	0.90	1.17	-0.28	-0.21	0.61	-0.49
France	0.20	0.46	0.39	-0.08	-0.08	-0.51
Italy	0.27	0.83	0.39	-0.03	0.11	-0.15
Japan	0.21	0.65	0.45	-0.08	0.02	-0.41
Netherlands	0.21	0.98	0.48	-0.10	0.01	-0.22
Norway	0.37	1.34	0.37	-0.09	0.30	-
Sweden	0.24	0.55	0.46	-0.11	0.12	-
U.K.	0.21	0.52	0.39	-0.06	-0.04	-0.33
U.S.A.	0.99	1.66	-0.48	-0.72	0.85	0.12
West Germany	0.15	0.43	0.49	-0.18	-0.22	-1.82

The cross price elasticities give a fairly consistent picture. There is a low degree of substitutability of coal for oil and a low degree also of oil for electricity except in Canada and the U.S. Coal and gas are strongly substitutable while coal and electricity are moderately substitutable. Gas appears to be complementary to both oil and electricity in many countries. Pindyck also calculates total price elasticities which allow for the additional impacts of a fuel price change on the substitution between energy and other factors of production. These are shown in tables 4.5 and 4.6.

Table 4.5: Pindyck's Total Own Price Elasticities for the Industrial Sector

	Coal	Fuel Oil	Gas	Electricity
Canada	-1.89	-1.03	-0.41	-0.61
France	-1.29	-0.34	-1.54	-0.54
Italy	1.63	-0.46	-1.37	-0.59
Japan	-1.49	-0.35	-1.54	-0.60
Netherlands	-1.78	-0.22	-1.48	-0.63
Norway	-2.15	-0.56	-	-0.62
Sweden	-1.44	-0.44	-	-0.60
U.K.	-1.35	-0.37	-1.44	-0.56
U.S.A.	-2.24	-1.17	-0.67	-0.63
West Germany	-1.31	-0.06	-2.34	-0.59

The own price total elasticities show a uniformly moderate value for electricity, while coal and gas tend to have much higher values. Oil has a surprisingly small value, but again this may reflect the period analyzed.

Table 4.6: Pindyck's Total Cross Price Fuel Elasticities for Industry

	C/O	C/G	C/E	O/G	O/E	G/E
Canada	0.69	1.08	-0.75	-0.29	0.14	-0.96
France	0.06	0.40	0.00	-0.13	-0.46	-0.89
Italy	0.09	0.76	-0.06	-0.10	-0.35	-0.61
Japan	0.07	0.60	-0.03	-0.13	-0.46	-0.89
Netherlands	0.09	0.92	-0.08	-0.16	-0.54	-0.77
Norway	0.15	1.33	-0.16	-0.09	-0.24	-
Sweden	0.07	0.54	-0.02	-0.12	-0.37	-
U.K.	0.06	0.45	-0.02	-0.12	-0.44	-0.74
U.S.A.	0.92	1.50	-1.03	-0.88	0.30	-0.43
West Germany	.05	0.41	0.01	-0.20	-0.70	-2.29

The total price elasticities are very different from the partial values and indicate that it is important to allow for substitution away from energy towards capital and labor. The resulting total picture shows very small substitution between coal and oil, coal and electricity and oil and gas except for Canada and the U.S.A., which over the estimation period were distinct in having domestic production of all three primary fuels. Coal is strongly substituted for gas but both oil and gas appear complementary to electricity.

There have been many subsequent studies of price elasticities for industry but few have attempted to give the range of results of Pindyck. Most have also concentrated on the translog cost function approach. For example, Uri [1979] pools sector and time series data (1960-71) for India using a translog cost function - the subsector coefficients were constrained to be equal. At the mean shares for each sector the own price elasticities for coal, oil and electricity were all negative while the cross price elasticities were all positive. The elasticities did show considerable variations between sectors due to the large differences in fuel shares between the sectors. Since the sectors were highly aggregated and very different (mining, transport, domestic, agriculture and commercial) this result is an immediate consequence of the translog form.

A series of studies by Sterner [89, 90] has looked at the economics of fuel switching within a single industry (cement) and a number of industries in Mexico. The cement study uses both aggregate time series on the industry and a cross section of sixty kilns in 1976 derived from a survey of fuel use. The cross section data allowed Sterner to relax the assumption of smooth and reversible substitution and use a 'putty-clay' approach as originally suggested by Johansen [1972]. Once capital is in place there is a fixed input requirement, while in choosing how much capital to have firms can choose over a range of inputs. Due to differences in technology between plants firms can still substitute ex post between inputs by varying the degree of capacity utilization (when there is spare capacity). Using this approach Sterner derives expressions for the short-run substitution of labor for energy. A similar exercise could be carried out as between fuels if the data were available. In essence this is the same approach as the power system analysis of Pinto and Besant-Jones. In his econometric study of manufacturing industry in Mexico, Sterner uses the translog cost function to a time series of cross sections for various industries. Not only were the partial price elasticities of substitution calculated but also those between energy and other inputs. Sterner compares his elasticities with others for developing countries and finds that his own price elasticities (at mean shares) are similar to those for industrialized countries but show a bigger difference against the values obtained by a variety of methods for developing countries. The absence of a standardized approach means that few general lessons can be drawn. More research, using Sterner's methodology on other developing countries is still needed.

Recently, new developments in functional form specification have appeared and these are especially valuable since they offer comparisons between model forms and between studies. Considine [1989] developed a logistic fuel share model, as explained in section 3, which has the advantage of imposing global concavity (although at the possible price of abandoning global symmetry). Its other distinctive feature is the stability of the elasticities with respect to fuel price changes. The translog function yields very different elasticities at different fuel shares (which is revealed by Griffin and Pindyck's results where the single model is evaluated at individual country shares). Hence if fuel prices change strongly then so will the elasticities at those prices. Considine defines a subsector "stationary fuel consumption" which is mainly the industrial sector less those subsectors where fuels are feedstocks (petrochemicals, plastics, steel). The data is from the U.S. for the period 1970 to 1985 and thus allows for some of the effects of the two oil shocks on fuel choice. The partial price elasticities for both the translog and logistic functional forms are calculated both at the mean shares for the period and for five year intervals. The effects of regulation are also incorporated in both models. Tables 4.7 and 4.8 give the own and cross price elasticities for the 2 models for 1970 and 1985 prices.

Table 4.7: Considine's Partial Price Elasticities for U.S. Stationary Fuel Combustion in 1970

(i) Translog

	Petroleum Products	Gas	Coal	Electricity
P	-0.01	0.08	0.21	-0.29
G	0.05	-0.58	-0.15	0.67
C	0.37	-0.44	-1.02	1.08
E	-0.08	0.31	0.17	-0.41

(ii) Logistic

	P	G	C	E
P	-0.10	0.14	0.10	-0.13
G	0.08	-0.55	-0.10	-0.58
C	0.26	-0.63	-0.68	1.04
E	-0.05	0.32	0.13	-0.40

Table 4.8: Considine's Partial Price Elasticities for U.S. Stationary Fuel Combustion in 1985

(i) Translog

	Petroleum Products	Gas	Coal	Electricity
P	-0.12	0.13	0.15	-0.16
G	0.09	-0.57	-0.17	0.66
C	0.5	-0.88	-0.12	1.44
E	-0.06	0.33	0.14	-0.41

(ii) Logistic

	P	G	C	E
P	-0.09	0.12	0.07	-0.10
G	0.09	-0.57	-0.13	-0.61
C	0.27	-0.64	-0.71	1.07
E	-0.04	0.31	0.11	-0.38

Two features are immediately apparent - the models give quite different results for certain fuel pairs e.g. the translog shows normal substitution between electricity and gas, while the logistic shows complementarity (interestingly Pindyck's partial elasticity between electricity and gas was also positive). The translog model also gives very variable elasticities for certain fuel pairs - coal and all other fuels are notable here, while the logistic yields very stable values. For neither model has symmetry been imposed. For ease of comparison Pindyck's translog partial elasticities for the U.S. are repeated in table 4.9.

Table 4.9: Pindyck's Partial Price Elasticities for U S. Industry

	P	G	C	E
P	-1.10	-0.72	0.97	0.85
G	-0.32	-0.52	0.72	0.12
C	0.99	1.66	-2.17	-0.48
E	0.11	-0.03	-0.06	-0.08

These are completely different from Considine's results for both 1970 and 1985 and suggest that the effect of pooling on the U.S. values may be very considerable. Considine does show that imposing an allowance for regulatory constraints does reduce the elasticities and this, plus the difference in the definition of the sector, must also be a contributory factor in explaining the variation in results.

A quite different approach to modelling energy price elasticities is exhibited in the work of Mountain and Hsaio [1989]. They disaggregate industry data to a regional level within Canada and by industry type (2 digit level). They also argue that, given the need to find a good approximation to the true cost function, it is not necessary to impose the same functional form on separate industries. They try different flexible functional forms in order to see which fits best in each case. In addition they introduce a wider range of possibilities for functional form by using both quasi quadratic Cobb Douglas and Fourier specifications. In addition they introduce an element of dynamic adjustment by fitting first order autoregressive error structures. The basic model however is again a two stage cost function which gives fuel shares in total energy and then relates total energy used to other factors of production. The data cover the period 1962 to 1979. The partial cross price elasticities are calculated for 1974 fuel shares and are shown in table 4.10. Coal was included with oil because of its minor importance. The model also allows for Hicksian technical progress. The results show that a single functional form cannot always be made to fit adequately (indicated by blanks in the table). Mountain and Hsaio compared their results with previous work on Canada and were able to conclude that in general their elasticities of substitution were larger. It is certainly noticeable that in comparison with the aggregate industry estimates of Pindyck and Considine, the use of disaggregated data plus an allowance for technical progress and for autocorrelation together produces very much higher values of the cross price elasticities. One important finding is that where quite different flexible forms are used the elasticities evaluated at the same fuel shares are close to each other. Also the results for the different industries are surprisingly close bearing in mind that no restriction has been placed to limit the results from the various industries. Mountain, Stipdonk and Warren [1989] using a similar methodology with data spanning 1962 to 1984 for Canada, reach similar conclusions.

Table 4.10: Mountain and Hsaio's Partial Cross Price Elasticities for Industries in Quebec for 1974

	Electricity/Oil		Electricity/Gas		Oil/Gas	
	Q	F	Q	F	Q	F
Food and Beverages	-	0.80	-	0.66	-	0.72
Tobacco	0.81	0.94	1.06	1.00	0.81	1.00
Rubber/ Plastics	-	.97	-	0.74	-	0.67
Leather	-	0.81	-	1.43	-	1.14
Textiles	-	0.78	-	1.02	1.40	
Knitting	0.79	1.00	1.00	1.00	0.79	1.00
Clothing	1.00	0.94	1.00	0.86	1.00	1.56
Furniture	0.94	-	0.94	-	1.08	-
Paper	0.94	-	1.10	-	0.91	-
Metal fabricating	-	0.92	-	0.80	-	1.15
Machinery	-	0.82	-	0.95	-	0.63
Non-metallic minerals	0.89	0.84	0.89	0.93	0.89	0.97
Petroleum products	0.80	0.80	1.02	0.72	0.80	1.25
Chemicals	-	0.89	-	0.97	-	1.00
Miscellaneous	0.96	1.00	1.00	1.00	0.96	1.00

(Q = quasi quadratic Cobb Douglas, F = Fourier)

This selection of estimated elasticities of inter fuel substitution shows that there certainly is no agreement in the values obtained. However this result needs careful interpretation. A key feature of all the models used is that (deliberately) they move away from the restrictiveness of a constant elasticity of substitution specification to one in which it can vary. Since in most models it varies with the level of fuel shares it will be very sensitive to relative prices. In this view there is no value in comparing elasticities from different studies or for different industries or countries unless they are evaluated at the same fuel shares. Where different functional forms have been fitted to the same data and evaluated at the same fuel shares, then the results of Mountain and Hsaio suggest that there may be a robustness in the elasticities which could allow the structural parameters of the model to be used to calculate elasticities at other fuel shares and in other situations.

Despite the substantial amount of econometric work that has been undertaken on estimating fuel elasticities certain limitations for their potential use in a wider content are very apparent:

(i) the studies are largely concentrated on the most industrialized countries and even when comparative values have been derived, as by Griffin and Pindyck, this has been on the basis of a single set of parameters evaluated at the fuel shares of the individual countries. No formal testing for differences between countries at the same fuel shares has been attempted;

(ii) much of the econometric work has used data which does not allow for the post oil shock period. There has apparently been no attempt to test for structural stability of the estimated models between (say) the pre and post 1980 period. Given that major movements in relative fuel prices may have taken place outside the estimation period of many models, it is not ideal to use elasticities based solely on earlier data;

(iii) rather little is known about the comparative behavior of different industries. However the work of Mountain and Hsaio suggests that, for Canada at least, the elasticities may be rather similar so that working with aggregate industry data may not suffer too greatly from potential bias caused by shifts in the relative importance of the various components.

(iv) very little attention has been paid to specific modelling of dynamic adjustment. The cross section work of Griffin by constraining all countries to lie on the same cost function can be seen as focussing on those long term differences which distinguish one country from another, and hence the values obtained may be more representative of long term elasticities than ones obtained from single country studies which exclude any dynamic factors. The problems of dynamic modelling, as explained by Mountain and Hsaio, cannot be easily overcome but this in general reduces the credibility of econometrically derived estimates of inter-fuel substitution.

One important issue that has received little attention in the econometric literature is the treatment of cases where one or more of the fuels is not used at all. As is clear from the international evidence, this is a common occurrence and is likely to be particularly important when using plant data (either in a cross section or a panel). The presence of zero observations in the dependent variable of fuel shares has been effectively ignored as a problem in most studies. Although the translog will always predict strictly positive shares if a finite fuel price is used as an explanatory variable, the error may not be too severe. However approaching the problem via the production function would lead to immediate difficulties since the fuel shares are related to the log of quantities (which are undefined for zero quantities). The problem with the translog cost function approach is to specify the price for the fuel where expenditure is zero. The simplest solution would be to use mean prices but this does not capture the reason for the non-use of the fuel. If prices really would be mean values for the plant in question then the fuel would be used, according to the model, to a substantial degree. Clearly the "true price" is so high that the fuel is above the switch point. Short of attempting to calculate the implicit price of the fuel at such sites, one solution would be to attach a high price (relative to the general country experience) and to experiment with values of this to see how closely the predictions of fuel share approach zero. Other methods would be to constrain the fuel shares by a Tobit type analysis - i.e. to hypothesize that there is a price above which the fuel would not be used and to attempt to recover this threshold from the data. The threshold can be made a function of own and competing fuel prices. Such an approach would be considerably more complex in computational terms than the simple translog fuel share equations.

The level of aggregation has important implications for the evaluation of the econometric models used. In an aggregate time series (for a single industry in a particular country) the data is all likely to be drawn from rather homogenous capital stock i.e. the composition of the capital will not change rapidly. The parameters of the model are thus likely to be very similar at all data points. As opposed to this the model will typically pick up short run responses to fuel price changes unless some explicit dynamic adjustment is included. In a cross section there is likely to be a wider spread of technology and hence a greater chance that the true parameters of the cost function vary between observations. If the observations are for countries (each aggregating over plants and industries) the averaging process may reduce this difference. At the same time differences in response between countries will be associated with persistent and long term differences in relative prices (due to local market conditions) so that the model would be more likely to capture long run substitution. Panel data (as used by Griffin) will combine the features of time series and cross section models. For those cross section studies where the unit of observation is a plant there can be very sharp differences in technology associated with the age of the capital stock. However the potential richness of such a sample might allow the use of a "vintage" approach to the production or cost function, which would essentially attempt to allow for the age of capital. The issue of separability would be crucial in determining whether separate cost share functions could be estimated for each vintage.

Problems of Using Estimates of Inter-Fuel Substitutability

For the policy purposes considered by this paper the key issue is the response of fuel use to a tax or subsidy induced price change. In order to encourage the use of gas as opposed to coal (say) in thermal power generation, a government could impose a tax on coal or give a subsidy to gas. This would be expected to change the fuel mix and hence the pollution characteristics of the power sector.

The analysis of the response to the change in taxes has four stages:

(i) an appreciation of the extent to which the tax would be fully passed on to the purchaser;

(ii) an estimate of the degree to which a non-taxed fuel would be substituted for the taxed fuel to produce the same output;

(iii) an estimate of the extent to which the higher average price of fuel would lead to a lower demand for all fuels;

(iv) an assessment of whether there would be further feedback effects, either through an induced change in the price of the non-taxed fuel or through macro-economic effects linked to the rise in fuel prices and the increase in government revenue.

Both the engineering approach and much of the econometric literature focus on the second issue of the size of fuel substitution elasticities at a given level of output. This is certainly likely to be the largest effect but the effects of non-infinite supply elasticities for fuels and of energy substitution elasticities as well as demand elasticities may be non-negligible in certain cases.

The elasticities of supply of the various fuels will depend both on market power and on the cost structure of the supplying industries. Where fuels are imported it is certainly true that any individual country can assume that the world supply curve is infinitely elastic. Where domestic supply is utilized it may be true that there is in effect a rising supply curve due to variations in cost conditions between different parts of the industry. In such a case shifts of demand curves along these supply curves will lead to changes in the supply price. The fall in the demand for the taxed fuel would tend to lower its price and the rise in demand for the untaxed fuel would tend to raise its price - both effects would tend to dampen the degree of fuel substitution. Similarly if the taxed fuel industry decided to absorb some of the tax rather than passing it all on, in order to protect its market share, then the initial stimulus to switch fuels would be blunted. The interaction between the demand and supply elasticities and the cross price elasticity measuring fuel substitutability can only be properly calculated using an articulated model of the supply and demand for the two fuels, in which the demands depend upon both prices.

The effect of the rise in the general energy price as substitution away from energy and towards capital and labor can be allowed for as indicated in section 3.9. This gives a further modification of the demand for both fuels which would interact with the supply equations if the supply elasticities are not infinite.

Other less important effects on the quantities of fuels used (and pollution created) are likely to arise from the macroeconomic feedbacks. The rise in energy prices will feed into inflation and hence into the real economy depending on the policy response of the government. At the same time the change in government revenue from taxation on the fuel will affect the budget balance and hence provide another link to the real economy. It is important to note that if the product is already taxed an increment in the tax rate can lead to a fall in total tax revenue (depending on the elasticity of demand). The introduction of a small tax is bound however to increase revenue.

It is clear from this brief discussion that the full effects on the quantities of fuels demanded of a rise in the tax rate on one of them requires a complex model to incorporate all the price effects. In order to use the results of such analysis it would be necessary to estimate not only the own and cross price demand elasticities, but also the supply elasticities for the competing fuels. An example of the analysis of the full impact of a fuel substitution tax in a macro-economic framework is provided by Hall, Truong and Anh [1990].

Assuming that the simplest possible model is a good approximation to reality i.e.:

(i) the tax rate is fully passed on to buyers;

(ii) the supply of both fuels is infinitely elastic over the range of demands experienced;

(iii) the impacts on the demand for the output (power or industry) through the impacts of the energy price change are negligible;

(iv) the impact on the demand for the product because of the change in the price of the aggregate energy input is negligible;

then the analysis of the impact of a change in the tax rate on one fuel requires, for a first approximation, the own price elasticity for the tax fuel and the cross price elasticities for the competing fuels.

Let the tax rate imposed be such that the price of fuel i at the burner tip rises by t_i percent. For an own price elasticity of e_{ii} the demand for fuel i will fall by (t_ie_{ii}) percent, while the demand for substitute fuel j will rise by (t_ie_{ji}) percent, where e_{ji} is the price elasticity of fuel j with respect to price i. These values can then be applied to the emissions characteristics to obtain the net change in pollution. To allow for energy substitution caused by the rise in the aggregate energy price it is first necessary to compute the percentage rise in the aggregate energy price - for small changes in the shares of different fuels this is a (constant) weighted average of the individual fuel price changes (where the weights are the original shares in total energy) so that if just price i changes then the aggregate energy price will change by (t_is_i), where s_i is the share of fuel i. With this change in the aggregate energy price and an own price elasticity for energy (versus other inputs) of E_i, the fall in the demand for energy will be $(E_it_is_i)$. The demand for all fuels will be reduced by this fraction thus contributing further to the reduction in the output of pollutants.

The use of this elasticity approach, as well as depending on the lack of feedback through supply responses and macro-economic effects, is limited by the limitations of the assumptions used in econometric modelling. Not only may the incorrect form of cost functions be used, but the lack of dynamic adjustment gives no indication of the timetable of the response. Elasticities drawn from engineering studies are likely to be more accurate for the plants from which the data were derived, but they too omit feedback effects. For example, virtually all engineering studies take demand levels and fuel prices as given. Allowing for the repercussions of fuel switching on the parameters of such models can lead to enormously complicated optimization where whole systems are involved. At a plant level indeed the feedbacks will usually be negligible - plants are rarely big enough to affect total fuel supply on economy wide demand - but a program designed to change the fuel mix over the whole of the power sector could produce economy wide effects.

From the policy standpoint, in which the costs of a tax based anti-pollution program would be crucial in deciding its feasibility, the great weakness of the econometric approach is its lack of specification of the associated capital costs. Not only the direct costs of investment in new capacity or conversion of existing capacity (unless multi-firing is in operation) will be important in the context of developing economies, the capital infrastructure required to transport the alternative fuel can be expensive. This will rarely be adequate before the fuel switching takes place so that inevitably there will be associated costs to take into account. The econometric approach as at present developed does not allow for directly associated capital costs to be included. Indeed the models used, as was noted in section 3, rely on the assumption that the fuel share choice is independent of capital costs. This shortcoming also implies that no distinction is made between ex ante (greenfield) choices, where an expansion is required, and ex-past choices where conversion is the issue. For both the estimated elasticity of substitution is the same - the same change in the price of one fuel relative to the other will produce the same predicted quantitative reaction for both situations. The strength of the engineering approach is that it forces the analyst to question the assumptions on fuel supply. If infrastructure needs to be provided (e.g. gas pipelines, compressor stations, peak storage facilities) by the investing body then the capital costs will enter the calculation, as will the element of operating costs which would be factored into the price of the fuel at the burner tip.

The preceding remarks could be taken to imply that there is no useful role for econometric models in designing pollution reduction strategies. This is to overemphasize their lack of detail in specifying the actual situation. In the past when fuel prices changed there would have been investment changes associated with whatever changes took place in fuel shares. The model in effect does not ignore the costs of the investment, but rather assumes that these costs relative to other costs were constant during the estimation period. Provided that this constancy continues to hold during the policy implementation period, then the price elasticities estimated allow for the associated capital costs of switching at historic average prices. The method will therefore be at its most misleading when the relative capital costs associated with fuel switching in the future are very different from those in the past, and also when the values during the estimation period themselves were highly variable. If, during the estimation period the capital costs of fuel switching were variable and no account is taken of this, then the estimated price elasticities will be biased because of the standard "omitted variables" effect of econometric theory. This effect is likely to be compounded in forecasting if the relation between capital cost to fuel cost movements changes from that of the estimation period. Hence a situation in which ex ante fuel substitution elasticities are estimated from data covering a period of expansion when the relevant capital costs are those for alternative plant on a greenfield site (plus associated infrastructure), while the future is of low growth in which there is ex past fuel switching through conversion of existing plant, will mean that the sensitivity of fuel choice to price changes is likely to be much lower in the future than the past. Thus, where all the relevant fuels have been used in the past and where the future capital cost structure is likely to be fairly similar to that of the past econometric estimates, econometric models may give a good guide to substitution possibilities despite their lack of detailed cost data.

The relative substitutability of fuels depends both on the unit fuel cost and the unit capital cost. Although these are clearly plant specific (depending on the size of the capital employed) various estimates have been given. A recent survey by Barnes [1991] compares different costs for generating electricity as shown in table 4.11.

Table 4.11: Costs of Electricity Generation by Type of Fuel

	Overall Efficiency percent	Capital Costs U.S. cents/kwh	Total Costs U.S. cents/kwh
Coal	33	2.0 - 4.3	3.8 - 6.9
Nuclear	32	3.8 - 10.0	5.3 - 11.8
Fuel Oil	33	2.0 - 2.5	4.8 - 5.7
IGCC	29	3.3 - 4.5	7.5 - 8.9
Gas Turbine	32	0.8 - 1.1	3.4 - 13.9
Gas CC	45	1.4 - 1.9	3.1 - 3.8

(IGCC - integrated coal gasification combined cycle
Gas CC - natural gas combined cycle)

This range of figures illustrates that the assumption of equal capital costs required for the standard econometric approach is rather doubtful for certain technologies. The relative importance of running costs to capital costs is also quite variable so that the choice of fuel will depend not simply on the relative fuel price but also on the relative capital cost. To the extent that changes in capital costs have been greater for some technologies than others over time then the choice of fuels may have been affected as much by shifts in relative capital costs as by shifts in relative fuel prices.

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